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Comparisons of Ultrasonic and Orifice Meter Responses to Wet Natural Gas Flow

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1. Introduction

Wet natural gas flow metering is important to natural gas production. Whereas there are multiphase wet gas meter designs available, due to economic constraints the majority of wet natural gas flows worldwide are still metered by single phase gas flow meter technologies. The orifice (DP) meter is one of the most popular gas meters for dry and wet gas flow applications. The ultrasonic meter ('USM') is a popular gas meter that is being strongly marketed for wet gas flow applications.

There is limited independent, neutral, 3rd party published information regarding the direct comparison of different gas meter design performance in wet gas flow service. 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. In this paper the wet gas flow performance of orifice meters and USMs are discussed, using 3rd party published information, and data taken from meters tested at the CEESI Wet Gas Test Facility.

2. Wet Gas Flow Terminology

Wet gas flow is a two-phase liquid and gas mixture flow where the Lockhart-Martinelli parameter (X_{LM}) is less or equal to 0.3, i.e. $X_{LM} \leq 0.3$ (see ISO [1, 2] & ASME [3]). The Lockhart-Martinelli parameter (eq. 1) is a non-dimensional term that quantifies the 'liquid loading', i.e. the relative amount of 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 gas and liquid densities respectively.

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

The gas to liquid density ratio ($DR = \rho_g / \rho_l$) is a non-dimensional expression of pressure. The gas densiometric Froude numbers (Fr_g), shown as eq. 2, is a non-dimensional expressions of the gas flow rate, where g is the gravitational constant, D is the meter inlet diameter and A is the meter inlet cross sectional area. When there is more than one liquid component (e.g. water and liquid hydrocarbon) the liquid density is considered to be the average of the liquid mixture.

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

"Water cut" is the ratio of the water to total liquid volume flow rates when the fluid is at *standard* conditions. "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 eq. 3, where m_w is the water mass flow rate and m_{lhc} is the hydrocarbon mass flow rate.

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

The average 'homogenous' density of a two component liquid mixture is calculated by eq. 4, where ρ_{lh} & ρ_w are the liquid hydrocarbon and water densities respectively.

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

Wet gas flow tends to cause gas meters to have a gas flow rate prediction positive bias. This bias is termed the 'over-reading' (or 'OR'). Eq. 5 shows the generic flow meter 'over-reading'. The term $m_{g,Apparent}$ denotes the erroneous uncorrected 'apparent' gas flow rate prediction from the gas meter.

$$OR = \frac{m_{g\ Apparent}}{m_g} \qquad \text{--- (5)}$$

$$OR\% = \left(\frac{m_{g\ Apparent}}{m_g} - 1 \right) * 100\% \quad \text{--- (5a)}$$

3. Wet Gas Flow Patterns

The flow pattern describes how the liquid phase is dispersed in the pipe / meter body. The meter's inlet flow pattern is dictated by many factors. For a given meter size and installation orientation (i.e. horizontal or vertical flow) the flow pattern is dictated by:

- how much liquid is present with a unit gas flow (i.e. X_{LM})
- the type of liquid (i.e. WLR_m), and
- the energy available with the gas to drive the liquid (i.e. the combination of DR & Fr_g)

For set wet gas flow conditions (i.e. given X_{LM}, WLR_m, DR, Fr_g values) the flow pattern is influenced by the meter orientation and pipe / meter size. For the case of orifice meters the local flow pattern through the meter is also influenced by the orifice meters β value.

Figs 1, 2, & 3 show three horizontal gas with light liquid hydrocarbon wet gas flow patterns photographed at the CEESI wet gas flow facility. Fig 1 shows stratified (or 'separated') flow. Here, relatively low gas energy, e.g. for a set DR a low Fr_g value, means the dominant influence on the liquid is the liquid's weight. Hence, the liquid runs as a river at the base of the pipe driven by the gas / liquid shear force. Fig 3 shows mist flow. Here, relatively high gas energy, e.g. for a set DR a high Fr_g value, means the dominant influence on

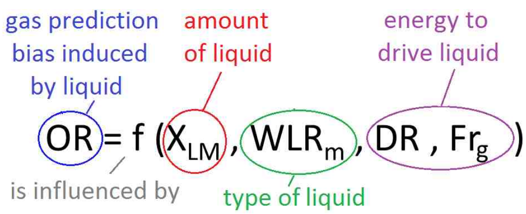
Fig 1. Stratified Wet Gas Flow.

Fig 2. Transitional Wet Gas Flow.

Fig 3. Mist Wet Gas Flow.

the liquid is gas dynamic pressure. Hence, the liquid flows as a mass of small droplets driven by the gas drag force on the droplets. Fig 2 shows a transitional flow pattern between stratified and mist flow. Here, moderate gas energy, e.g. for a set DR a moderate Fr_g value, means the flow pattern is between the stratified and mist flow patterns. In reality a horizontal wet gas flow pattern can be anywhere on the spectrum between stratified, transitional, and mist flow depending on the flow conditions.

The wet gas flow pattern, i.e. the liquid dispersion in a pipe and into the meter body, dictates what the meter sensors 'see' and therefore how the meter responds to the presence of the liquid. For a given gas meter design and geometry, the inlet flow conditions dictate the inlet flow pattern, and hence the meters response to the wet gas flow. Gas meter wet gas flow correlations tend to therefore be of the form:



Industrial wet gas metering applications will usually have varying flow conditions, and therefore corresponding changes in flow patterns, over the service time of the meter. It is therefore not practical to use a gas meter that only operates with a specific flow pattern. A gas meter in use in a wet gas flow application must be able to cope with any flow pattern. It would be unreasonable of a meter supplier to demand the meter user supplies a specific wet gas flow pattern regardless of his operational requirements.

4. <u>Orifice DP Meter & Ultrasonic Meter Wet Gas Response</u>

Wet gas flow is an extremely adverse flow condition for **all** gas meter designs. The question should not be which gas meter design has the ***best*** response to wet gas flow. They all have a relatively poor performance. The question should be which gas meter design manages to deliver the most useful amount of information about the wet gas flow.

4a. <u>Orifice (DP) Meter Wet Gas Response</u>

The response of orifice meters to wet gas flow has been actively researched for sixty years. This response is now so well understood that ISO has published an orifice meter wet gas correction factor (i.e. 'correlation). The existence of an ISO orifice meter wet gas correlation states that the orifice meter wet gas response is well understood, reproducible, and accurately predicted. (The lack of a wet gas flow meter correlation for any meter implies the opposite is true.) ISO states that the wet gas OR is related to:

- the X_{LM} (see Fig 4)
  for all other parameters held constant an increasing X_{LM} causes an increase in OR
- the DR (see Fig 5)
  for all other parameters held constant an increasing DR causes a reduction in OR
- the Fr_g (see Fig. 6)
  for all other parameters held constant an increasing Fr_g causes an increase in OR
- the orifice β (see Fig. 7)
  for all other parameters held constant an larger β causes a reduction in OR
- the WLR_m
  for all other parameters held constant an increasing WLR_m causes a reduction in OR

ISO TR 12748 [2] gives an orifice meter wet gas correlations for horizontally installed 2" to 4" orifice meters. This correlation reproduced here as equation set 6 thru 12. It relates the orifice meter wet gas over-reading (OR) to the Lockhart Martinelli parameter (X_{LM}), the water liquid mass ratio (WLR_m), the gas to liquid density ratio (DR), and the gas densiometric Froude number (Fr_g). Therefore, as X_{LM}, WLR_m, DR, & Fr_g dictate the flow pattern, the ISO correlation automatically accounts for the influence of the flow pattern.

This ISO orifice meter wet gas correlation was developed and checked over many years by cross industry cooperation (including multiple operators, meter manufacturers, Joint Industry Projects and test facilities). Figs 8 thru 11 show photographs of various 2" to 4" orifice meter wet gas flow tests carried out by industry in the last decade. This ISO orifice meter correlation is valid for all paddle plate, single & dual chamber orifice meter designs from all manufacturers of ISO 5167-2 compliant meters. The ISO wet gas orifice meter correlation was

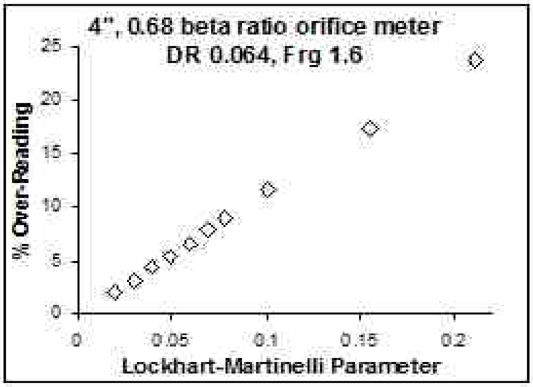


Fig 4. The Liquid Loading Effect.

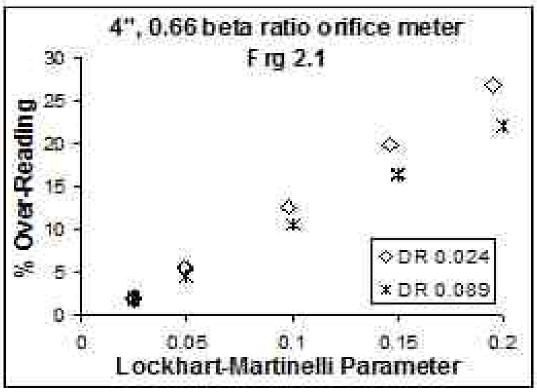


Fig 5. DR Effect.

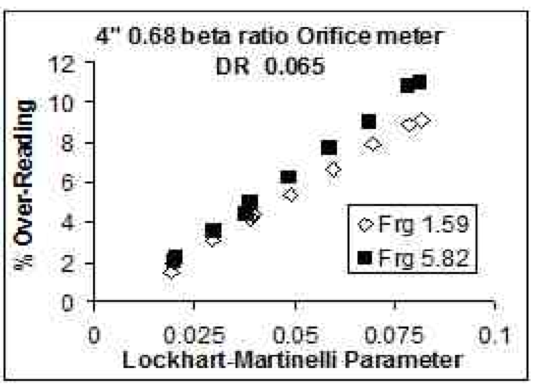


Fig 6. Fr_g Effect.

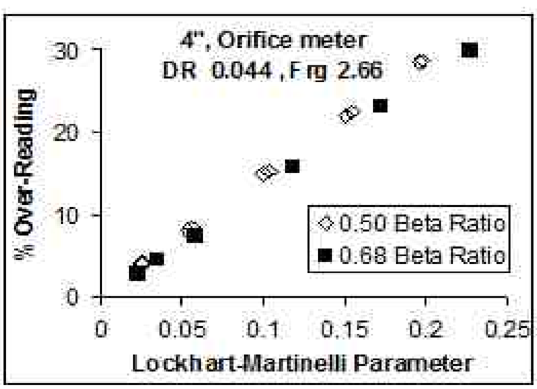


Fig 7. The Beta Effect.

$$\dot{m}_g = \frac{\dot{m}_{g,apparent}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \quad \text{--- (6)}$$

$$C = \left(\frac{\rho_g}{\rho_l}\right)^n + \left(\frac{\rho_l}{\rho_g}\right)^n \quad \text{--- (7)}$$

$$Fr_{g\,strat} = 1.5 + (0.2 * WLR_m) \quad \text{-- (8)}$$

$$\# A = 0.4 + \{-0.1 * (\exp(-WLR_m))\} \quad \text{-- (9)}$$

$$n_{strat} = \left\{\left(\frac{1}{\sqrt{2}}\right) - \left(\frac{\# A}{\sqrt{Fr_{g,strat}}}\right)\right\}^2 \quad \text{-- (10)}$$

$$n = n_{strat} \quad \text{for } Fr_g \le Fr_{g,strat} \quad \text{-- (11)}$$

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

-- (12)

Wet gas orifice meter data independent to that used by ISO 12748 is now publicly produced by industry wide collaboration, i.e. by industry for industry, and is 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.

Fig 12 reproduces a massed orifice meter wet gas data set (see Steven et al [4][1]) 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.

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[1] Steven et al [4] also describes in detail evidence that the orifice meter does not cause damming problems and the DP signal is pseudo steady.


Fig

Fig 8. CEESI 4” Orifice Meter
Wet Gas Test.

Fig 9. CEESI 2” Orifice Meter
Wet Gas Test.

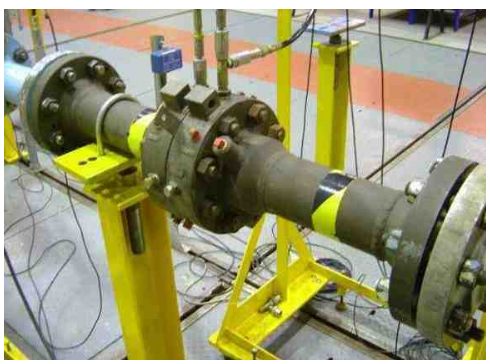

Fig 10. TUVNEL 4” Orifice Meter
Wet Gas Test.

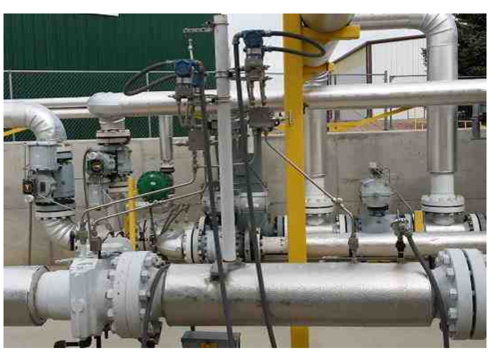

Fig 11. CEESI 8” Orifice Meter
Wet Gas Test.

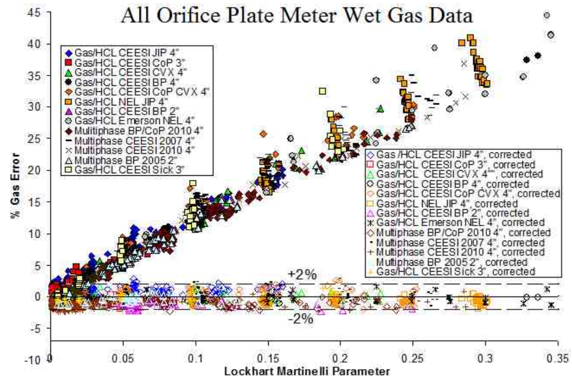

Fig 12. Massed 2” to 4” Orifice Meter Wet
Gas Data With & Without the ISO
Correlaton.

Parameter	Range
Pressure	6.7 to 78.9 bara
DR range	0.0066 < DR < 0.111
Fr_g range	0.22 < Frg < 7.25
X_{LM}	$0 \le X_{LM} < 0.55$
Inside full bore dia.	1.94” ≤ D ≤ 4.026”
Beta	0.341 ≤ β ≤ 0.683
Gas / Liquid phase	Gas / LHC/ Water

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

available. The data within the ISO correlations range (see Table 1) has reinforced the correctness of the ISO correlation. Data outside the range has shown the robustness of the ISO correlation. For example, in 2014 BP (Steven et al [5]) showed CEESI 4” wet gas orifice meter data where the liquid components included water, hydrocarbon liquid with heavier components (22% at ≥ C30+) that would form wax below approximately 97^{0}F, and MEG. Although the ISO orifice meter wet gas correlation was extrapolated to different fluid properties it was shown to operate within the stated uncertainty. Massed CEESI 8”, 0.689β orifice meter wet gas flow data was also shown. Extrapolating to the larger 8” meter size only increased the ISO correlations gas flow rate prediction uncertainty from 2 to 3% at 95% confidence.

All gas meters are designed for use in single phase gas flow applications where they predict a gas flow rate, not a gas and liquid flow rate. When used in wet gas service this gas flow rate prediction is wrong as the liquid induces a positive bias, i.e. an over-reading. There is no liquid flowrate prediction. Gas meter wet gas correlations (such as the ISO orifice meter wet gas correlation) can correct gas flow rate bias only for a known externally supplied liquid flow rate. This is the Achilles heel of using gas meters in wet gas service. In most cases the end user has no way of knowing what this liquid flow rate is. However, unique amongst gas meter designs, the orifice meter offers the end user a simple way to predict the liquid flow rate. No other meter has any practical way of doing this. The Venturi meter can operate with the same concept but has a significantly smaller liquid loading range. This method is now discussed.

4a.1 Orifice Meter: PLR vs. X_{LM}

An orifice meter can have a downstream pressure tap that allows the operator to measure the permanent pressure loss (or 'PPL') across the meter, i.e. DP_{PPL} (see Fig 13). The ratio of the PPL (DP_{PPL}) to the flange tap standard 'traditional' DP (i.e. DP_t) is called the 'Pressure Loss Ratio', or 'PLR'. It was shown by de Leeuw [6] for Venturi meters and then Steven et al [4] for orifice meters (with $\beta \geq 0.5$) that the PLR is influenced by the liquid loading (i.e. the Lockhart Martinelli parameter).

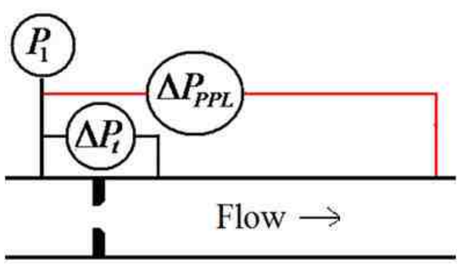

Fig 13. Sketch of Orifice Meter With Downstream Pressure Port.

Fig 13 reproduces a graph from Steven et al [4] showing the relationship between the PLR and Lockhart Martinelli parameter for a 4", 0.68β orifice meter. ISO have subsequently produced a Lockhart Martinelli parameter prediction equation published in ISO TR 11583 [1]. This ISO orifice meter equation relates the liquid loading to the discharge coefficient, beta, PLR, and the flows density ratio, i.e.

$X_{LM} = f(C_d, \beta, DR, PLR)$

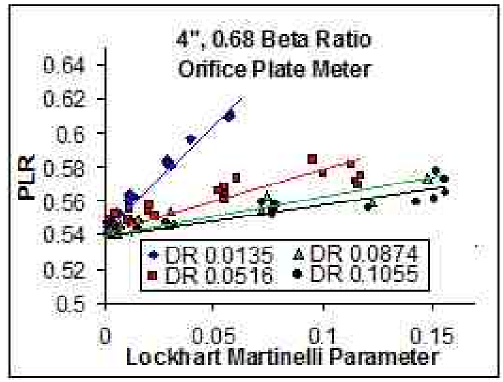

Fig 14. Orifice Meter PLR vs. X_{LM}

Although this ISO method is restricted in the flow conditions in which it is applicable (see ISO TR 11583 [1]) it works across reasonable range of flow conditions and is valuable to industry. ISO TR 11583 [1] states when used within the applicable range, combining this liquid loading prediction in conjunction with the orifice meter wet gas correction factor (i.e. equation set 6 thru 12) the gas flow rate is predicted to 6% and 95% confidence. Fig 14 shows the results from applying this ISO technique to the published CEESI 4", 0.68β orifice meter.

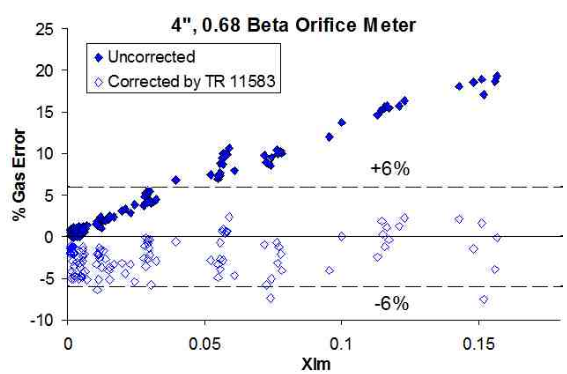

Fig 15. 4", 0.68β Orifice Meter Wet Gas Data.

Industry knows a lot about an orifice meters reaction to wet gas flow. The generic orifice meter wet gas flow response is not just repeatable, but reproducible, and therefore remarkably predictable. Industry has no equivalent detailed knowledge of any other gas meter's reaction to wet gas flow.

4b Ultrasonic Meter Wet Gas Response

The response of ultrasonic meters (USMs) to wet gas flow has been sporadically researched by competing manufacturers. There is no 'standard' USM design. Different manufacturers have different USM designs, some clamp-on, some integral meters, with different numbers of paths, different path locations, different transducer designs and different software. Hence, unlike orifice meters 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.

A 1998-2002 CEESI wet gas JIP tested a first generation (now obsolete) three bounce path USM design with various wet gas flow conditions and flow patterns. As the wet gas flow liquid loading increased this USM had an increasing gas flow rate over-reading (with significant scatter) until a Lockhart-Martinelli parameter of 0.07. AT higher liquid loadings this USM output became very erratic and unpredictable. The JIP rotated the meter around one bolt pattern to change the location of the paths relative to the liquid dispersion and found that this altered this meters performance. These results are discussed in detail by Steven [7].

In 2013 a 3rd party asked CEESI to wet gas flow test 8" meters in series. These included:

- clamp-on bounce path ultrasonic meter (see Fig 16),
- 3 bounce path ultrasonic meter (see Fig 17),
- chordal four path (Westinghouse) ultrasonic meter (see Fig 18),
- 0.689 beta orifice meter (see Fig 11).

Table 2 shows the wet gas test range.

The clamp-on USM had two sets of transducers each producing a bounce path. One path was a vertical path (and

Fig 16. 8" Clamp On USM Wet Gas Tests

Fig 17. 8" 3 Bounce Path USM Wet Gas Testing

Fig 18. 8" Chordal USM Wet Gas Testing

Fig 19. 4", Chordal 4 Path USM Under Wet Gas Testing

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}	$0 \le X_{LM} < 0.16$
Inlet Diameter	7.625" ≤ D ≤ 7.981"
Gas / Liquid phase	Gas /HCL/ Water

Table 2. CEESI 8" Multiple Flow Meter Wet Gas Flow Test Range.

other was a horizontal path. The transducers supplied were not rated for the lowest pressures of the test and therefore only the higher pressure data was recorded. The dry gas response was good, matching the facility reference to 1%. However, this clamp-on meter was severely affected by wet gas flow. Fig 20 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.

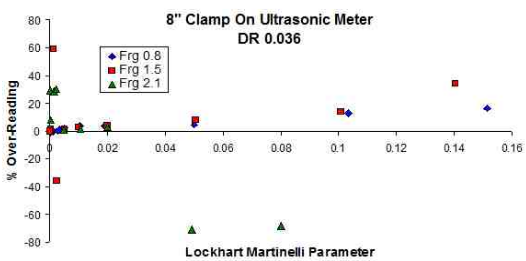

Fig 20. 8" Clamp-On USM Wet Gas Data

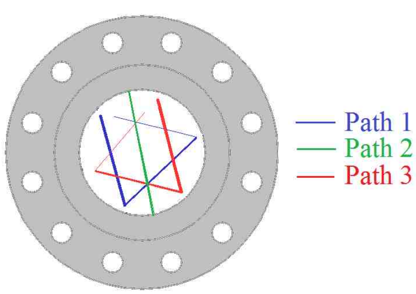

Fig 21. 8" Bounce Path Configuration

The 8", 3 bounce path ultrasonic meter had two double bounce paths and one single bounce path. These paths are shown in Fig 21. The USM 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 dry gas

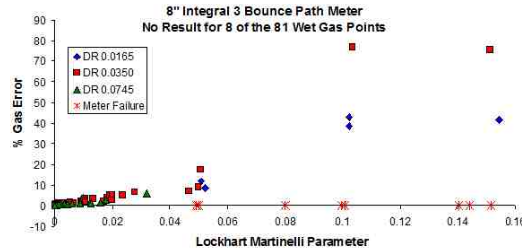

Fig 22. 8", 3 Bounce Path USM Wet Gas Data.

performance matched the gas flow reference 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 in Fig 22 show that this is the case. For eight of the eighty six wet gas data points recorded (approximately 9% of the data) this meter failed to produce any gas flow rate prediction. These meter failures began to appear at $X_{LM} > 0.05$. Of the test points where the meter gave a gas flow rate prediction there was significant random scatter.

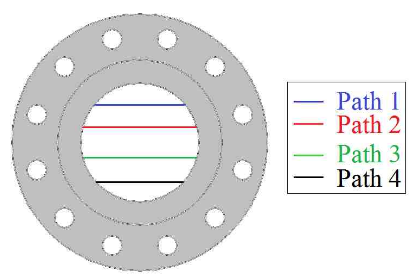

Fig 23. Sketch of a Four Chordal Path Ultrasonic Meter (not to scale)

Fig 18 shows this USM installed in the CEESI wet gas test facility. Fig 23 shows a sketch of an 8" chordal four path (Westinghouse design) USM design. Each path is at a set height in the horizontally installed meter body. Hence, for wet gas flows, the lower the path the more likely it will encounter higher liquid concentrations. This USMs dry gas flow performance matched the gas flow reference to <1%. Figure 24 shows the wet gas flow performance. A general relationship exists

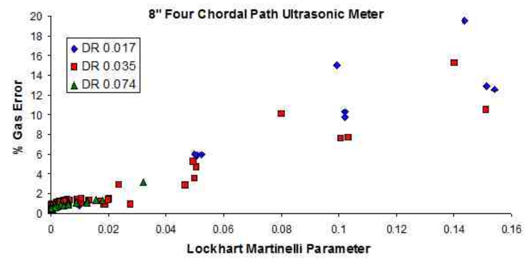

Fig 24. 8", 4 Chordal Path USM Wet Gas Data

between increasing liquid loading and increasing 'over-reading'. However, there is considerable scatter in the data. Unlike for orifice meters, no gas to liquid density ratio or gas densiometric Froude number effects was evident.

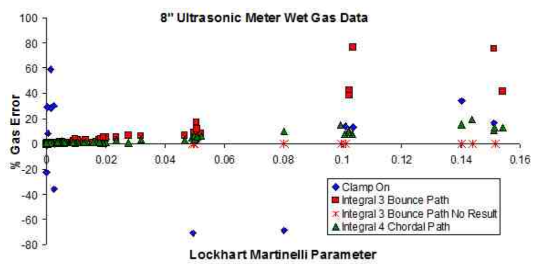

Fig 25. All USM Wet Gas Data

Fig 25 shows the performance of the different 8" USM designs tested together. The 8" chordal four path USM had less scatter and generally lower gas flow rate prediction error than the other USM designs.

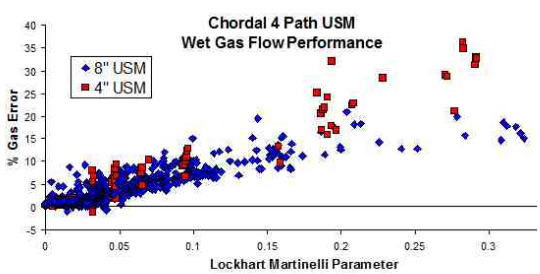

Fig 26. 4" & 8" Four Path USM Wet Gas Data.

However, Fig 26 shows a comparison in 4" and 8" chordal four path meters of the same design. There is a difference in over-reading at higher liquid loadings, i.e. any chordal four path USM wet gas correction would need to be for specific meter sizes.

At the time of writing there is no ISO (or other standards board) standard or technical report offering a USM wet gas correlation. No USM manufacturer has as yet produced a wet gas correlation for any specific USM meter design. Operators of USMs in wet gas applications have to accept the bias induced by the liquids presence or attempt to create their own correction.

5. Orifice & Ultrasonic Meter Wet Gas Response Comparison

To review the orifice and USM wet gas flow performance in proper context it is beneficial to compare these meters tested in series. Unfortunately such comparison data is rare.

A comparison of 8" chordal four path ultrasonic & orifice meters installed in series at the CEESI multiphase wet gas facility (see Figures 18 & 11 respectively) is shown in Figure 27. A comparison of 4" chordal four path ultrasonic & orifice meters installed in series at the CEESI multiphase wet gas facility (see Figures 19 & 8 respectively) is shown in Figure 28.

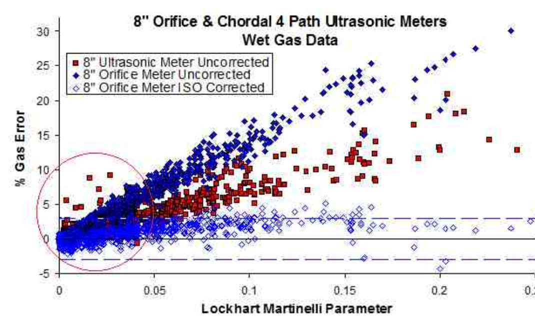

Fig 27. 8" Orifice & Ultrasonic Meter Wet Gas Data Comparisons.

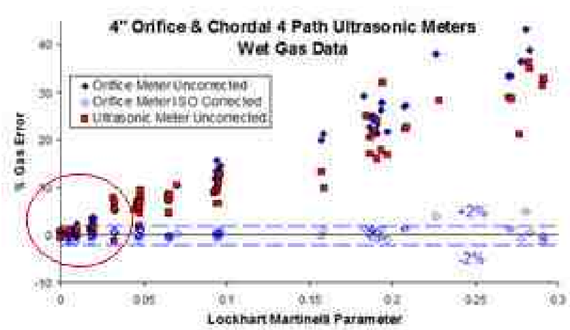

Fig 28. 4" Orifice & Ultrasonic Meter Wet Gas Data Comparisons.

The 8” USM over-reading tended to be slightly smaller than that of the orifice meter but both have substantial gas flow rate errors. The 4” USM and orifice meters had similar substantial wet gas over-readings. In most applications such errors will need to be corrected, and hence it is often not the comparison of the substantial uncorrected over-reading that is of importance, but the availability and performance of respective wet gas correlations. The orifice meter has the ISO TR 12748 orifice meter correlation available. This correlation is technically for ≤ 4” orifice meters but it can and is extrapolated to larger orifice meters. It is now known that for a known liquid flowrate extrapolating this correlation to 8” orifice meters predicts the gas flowrate to 3% at 95% confidence (e.g. see Fig 27). Fig 28 shows the 4” orifice meter wet gas over-reading corrected (for a known liquid flowrate) to 2% uncertainty at 95% confidence. There are no standards board or manufacturer published USM wet gas correlations. Therefore unlike the orifice meter there is no equivalent ultrasonic meter wet gas correlation with which to correct this ultrasonic meter’s over-reading. Hence, Figs 27 and 28 only show orifice meter corrections.

When a gas meter is used in low liquid loading wet gas applications the operator may simply hope that the over-reading is negligible. In this case the gas meter design with the lowest over-reading would be desirable. Figures 27 and 28 have circled wet gas liquid loading regions of interest in such a scenario. The 4” USM and orifice have similar over-readings at low liquid loading. The 8” USM tends to have on average a slightly smaller over-reading than the orifice meter but the significantly higher level of USM scatter negates any significant advantage in this respect. The USM can’t be guaranteed to 95% confidence to have a lower over-reading in this low liquid loading region.

In some applications the operator may not know if the gas is wet. Common methods external to the meter of checking for wetness, and possible liquid loading, include test separator history or tracer dilution techniques. However, these are spot checks. In cases where the meter does not meter (a quantitative check) or even monitor (a qualitative check) the liquid flow, or liquid loading, the meter operator does not know when the liquid loading changes between routine scheduled checks. Therefore, a wet gas metering or monitoring system internal to the meter is desirable.

Section 4a1 described ISO’s methodology for predicting the liquid loading through an orifice meter. Whereas the USM does not as yet have such an equivalent method, it does have a well-known diagnostic system. In this final section the use of the USM and orifice meter diagnostic systems to monitor changes in wet gas liquid loading is described.

6. Liquid Loading Monitoring

6a. Orifice Meter Verification System ‘Prognosis’ Used For Liquid Monitoring

Modern orifice meters have a comprehensive verification / diagnostic system. Using the concept of pressure field analysis across the orifice meter the ‘Prognosis™’ system monitors for any orifice meter system problems. This includes meter body, instrumentation, or flow condition issues. However, if there is a *known* specific problem, such as wet gas flow, the operator can use this diagnostic tool to monitor the wet gas flow through the orifice meter.

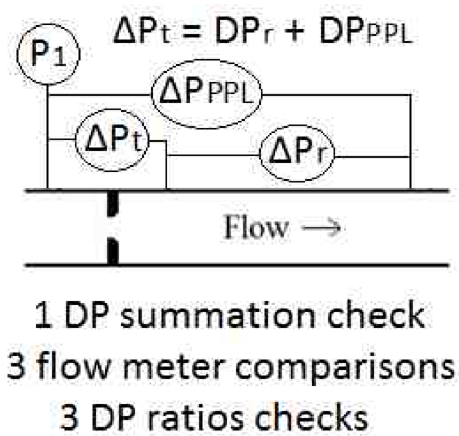

Fig 29. Prognosis Verification System Set Up for an Orifice Meter.

Fig 29 shows the DP instrumentation set up for Prognosis. Along with the traditional DP read across the plate (DP_t) there is a third pressure tap downstream of the plate. This allows the reading of a permanent pressure loss, or 'PPL' (DP_{PPL}), and a recovered DP (DP_r). The traditional DP (DP_t) is the sum of the recovered (DP_r) and the PPL (DP_{PPL}). This relationship gives a diagnostic check on the integrity of DP readings.

The three DPs allow three independent gas flow rate predictions to be made, from traditional flow rate (DP_t based), expansion flow rate (DP_r based), and PPL flow rate (DP_{PPL} based) equations. These equations are derived in detail by Steven [8]. That is, Prognosis effectively makes and orifice meter three flow meters in series. There is the primary meter with two check meters. This allows three independent flow rate prediction checks, i.e. three diagnostic checks.

Reading three DPs allow three DP ratios to be found. These DP ratios are effectively constant values dictated by the orifice meter geometry. The found DP ratios can be compared to the predicted baseline values. This is three more diagnostic checks.

Flow meter diagnostic display is an important issue. A complicated display can make the meaning to the average meter operator difficult to understand. Hence, Prognosis has a simple display screen. Fig 30 shows an actual Prognosis output display from a correctly operating gas flow 4" orifice meter (see Fig 8). There are four points, three with x & y coordinates, and one with a single x coordinate, i.e. seven values from the seven diagnostic checks.

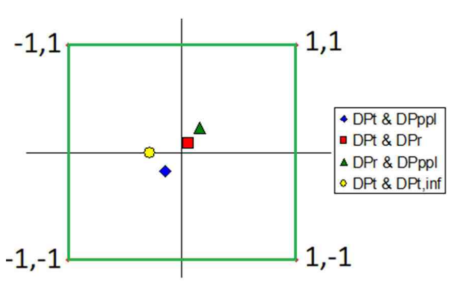

Fig 30. Orifice Meter Prognosis Display.

Points with both x (abscissa) and y (ordinate) values are from particular pairs of DPs. The abscissa shows the flow rate comparison result, the ordinate shows the DP ratio result. The abscissa value only point is the DP summation check. All seven diagnostic values are normalised. This results in the display presented in Fig 30. The end user only has to understand "in box good / out box bad".

The result shown in Fig 30 is for a serviceable orifice meter with no problems. This is the normal common result. However, Fig 31 shows the Prognosis result from a 4", 0.68β orifice meter tested with wet gas flow at CEESI. The tests used natural gas & Exxsol D80 (a light liquid hydrocarbon) Here the density ratio was 0.0135, and the gas densiometric Froude number was 1.4. Prognosis clearly trends changes in wet gas liquid loading. At all times the DP summation showed no problems with the DP readings.

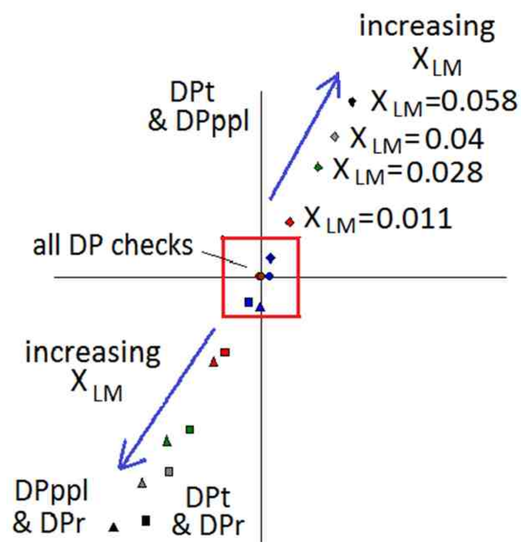

Fig 31. CEESI Wet Gas Flow Test of a 4", 0.68β orifice meter.

Fig 32 shows a 4", 0.7β orifice meter installed by an end user on a plunger lift well in Texas, US. Note the downstream tap and extra DP readings facilitating the use of Prognosis. Fig 33 shows the field results. As the plunger lift cycle progresses the liquid loading of the wet gas flow reduces, and the Prognosis result tracks this. As the wet gas gets drier the points tend towards the origin. At all times the DPs read are shown to be correct.

Fig 32. Orifice Meter with Prognosis on a Plunger Lift Well.

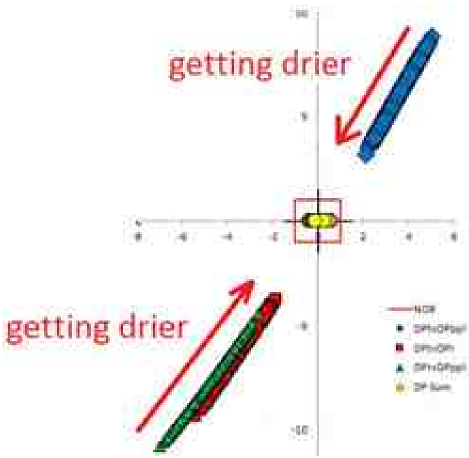

Fig 33. Orifice Meter with Prognosis on a Plunger Lift Well.

Wet gas flow causes the particular Prognosis pattern shown in Figs 31 and 33. This is not a pattern unique to wet gas. There are a select few other problems that can cause this type of display pattern. However, unique to wet gas flow is this pattern coupled with all 3 DP readings having high standard deviation. That is, Prognosis can identify wet gas as the specific problem and monitor the liquid loading.

6b. <u>Chordal 4 Path Ultrasonic Meter Liquid Loading Monitoring</u>

USMs have a generic comprehensive diagnostic system consisting of the following diagnostic checks:

- Speed of Sound,
- Path Velocity Ratios
  - usually shown individually,
  - as Profile Factor, &
  - Symmetry,
- Path Performance,
- Path Turbulence,
- Path Signal to Noise Ratio, and
- Path Gain.

The USM diagnostic result, i.e. "diagnostic pattern", produced by cross referencing these seven diagnostics can potentially indicate wet gas flow. However, there is less literature regarding the generic USM diagnostic system's reaction to wet gas flow than there is for the orifice meters Prognosis system. This is in part due to the fact that there is significantly less general wet gas flow R&D on USMs than orifice meters. Another hindrance to understanding USM diagnostic wet gas flow response is the variation of different manufacturers USM diagnostic display designs. Physically similar USM designs (such as two competing chordal 4 path designs) will have similar wet gas diagnostic responses, but due to differences in the display layout the response may not be obviously similar.

The following example shows an 8" chordal 4 path USM's diagnostic results when tested with wet gas flow at CEESI (see Fig 19). The tests used natural gas & Exxsol D80 at a density ratio of 0.045 and a gas densiometric Froude number of 2.2. The liquid loading range was $X_{LM} \leq 0.07$ (i.e. similar to the orifice meter wet gas data shown in Fig 31).

Fig 23 identifies the chordal four path USM path numbers. Figs 33a thru 33d shows the USM path velocity ratios vs. X_{LM}. Path 4 (the lowest path) begins to show a slower than expected velocity by a Lockhart Martinelli parameter test point of 0.017. However, this change may be rather subtle for a typical end user to pick up. It has become more obvious by a Lockhart Martinelli parameter test point of 0.032.

Fig 34 shows the individual path performance vs. liquid loading (i.e. X_{LM}).

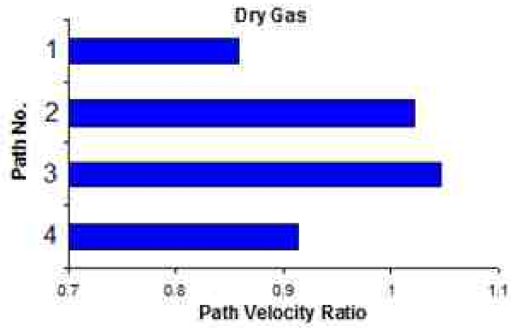

Fig 33a

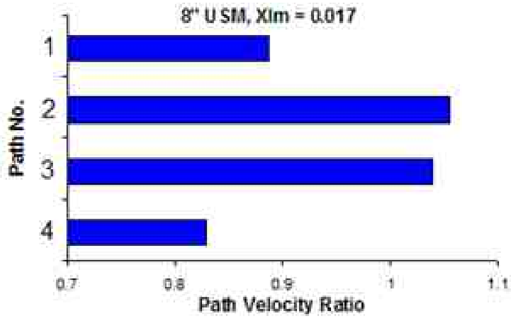

Fig 33b

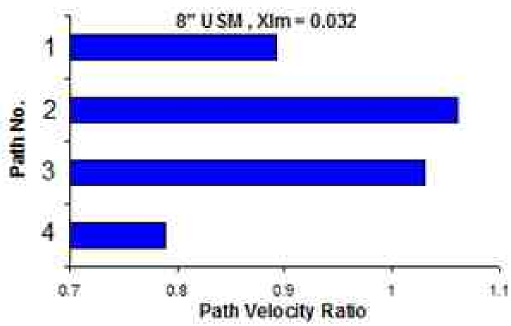

Fig 33c

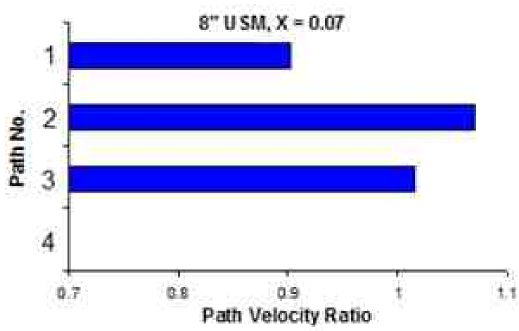

Fig 33d

Path 4 begins to fail at about $X_{LM} \geq 0.015$. Path 3 begins to show performance drop off at about $X_{LM} \geq 0.03$.

Fig 35 shows the 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.

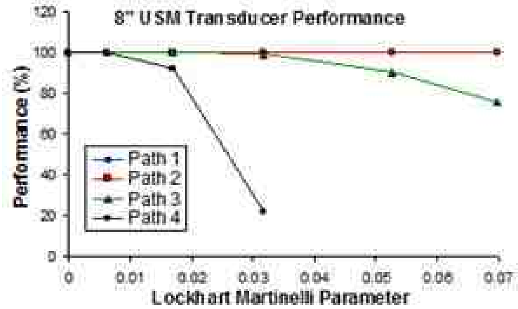

Fig 34. 8" USM Performance % vs. X_{LM}

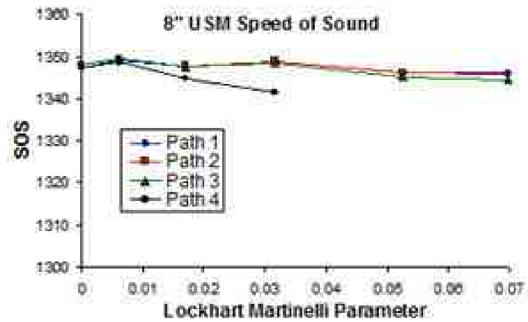

Fig 35. 8" USM SoS check vs. X_{LM}

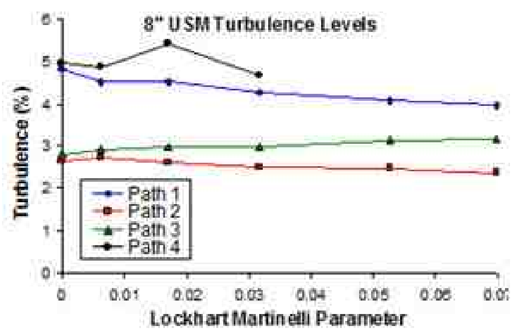

Fig 36. 8" USM Turbulence % vs. X_{LM}

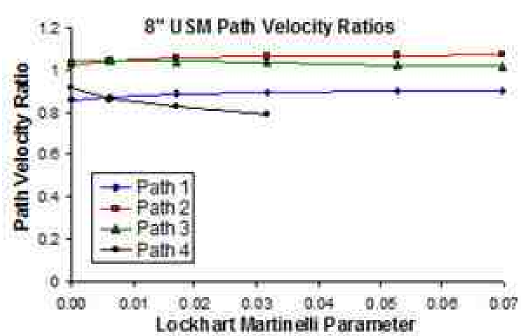

Fig 37. 8" USM Path Velocity Ratio vs. X_{LM}

Fig 36 shows the path turbulence vs. liquid loading. No clear indication of a problem is evident until Path 4 fails at $X_{LM} > 0.03$. Across the liquid loading range tested no other paths turbulence diagnostic check noticed the presence of wet gas.

Fig 37 shows the Path Velocity Ratios vs. liquid loading. This is the same data as in Fig 33a to 33d plotted in a different format. The path velocity ratio does contain some information but it is difficult to see from this form of plot. A clearer plot is the Profile Factor vs. Symmetry plots (see Fig 38). Here, the increasing liquid loading moves the point out the box of normal operation towards the upper right. Whereas this result does not specifically show wet gas it does clearly show there is an unspecified problem. If the meter operator knew he had a wet gas issue from external sources this plot allows USM wet gas liquid loading monitoring.

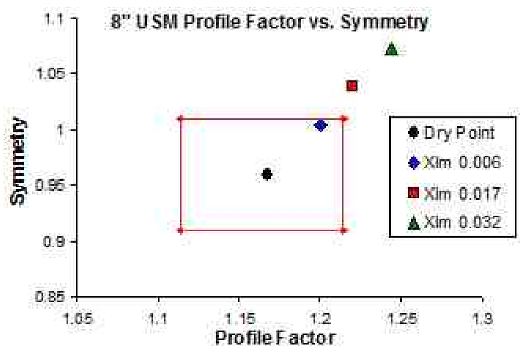

Fig 38. 8" USM PF vs. Symmetry

The USM wet gas flow diagnostic results shown here come from a USM deliberately tested with wet gas flow. It is therefore tempting, but wrong to state this USM "saw wet gas flow". It "saw" an unspecified problem. In the field an operator may not expect wet gas flow. In this common scenario the operator will not see plots of diagnostic parameter vs. liquid loading. He will only see the raw diagnostic output values. It is for the USM manufacturers to produce diagnostics that are capable of *specifically* identify wet gas flow from other potential sources of problems. Without this it is up to the skill of the operator to decipher the cause of the alarm. Some, but not all USMs presently have a wet gas alert.

7. Conclusions

Wet gas flow is an adverse flow condition for **all** gas meter designs.

Orifice meter wet gas performance is so well understood and reproducible that ISO has an orifice meter wet gas correlation. Hence, for a known liquid loading industry can correct the orifice meter wet gas over-reading. For limited flow conditions ISO has an orifice meter liquid loading prediction. Also, there is a commercial system for orifice meters (Prognosis) that supplies diagnostics, inclusive of wet gas liquid loading trending. This system is useable by rudimentary trained operators. Although not widely advertised the orifice meter is one of the most capable gas meter designs for use in wet gas flow applications.

Different USM designs have different wet gas performances. Modern 4 path chordal USM designs seem to have the most reproducible wet gas performance of USM designs, with gas flow rate over-readings induced by the presence of liquid. However, unlike generic orifice meters neither ISO nor any USM manufacturer has yet published an USM wet gas correlation, or any method of predicting the wet gas liquid loading through the meter. Hence, as yet it is not possible to correct an USM over-reading for a known liquid loading. However, the USM has a diagnostic system that is potentially capable of identifying the existence of an unspecified problem when the gas is wet. When the flow is known to be wet a skilled trained USM operator may be able to use the USM diagnostics to monitor liquid loading trends.

8. References

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