

Horizontally Installed Orifice Plate Meter Response to Wet Gas Flows

Richard Steven, Colorado Engineering Experiment Station Inc.

Gordon Stobie, ConocoPhillips Company

Andrew Hall, BP Exploration Operating Company, Ltd.

Bill Priddy, BP Exploration Operating Company, Ltd.

1. Introduction

The research and development of multiphase wet gas flow meters for natural gas flows with entrained hydrocarbon liquid (HCL) and water is important to industry. However, the performance of single phase flow meters, such as orifice plate meters, with multiphase wet gas flows is also of importance. Nevertheless, in recent years research into orifice meter wet gas flow response has been relatively underplayed.

There are several reasons why orifice meter response to multiphase flow is important. Multiphase meter flow rate predictions can be compared to separator system flow rate measurements. Separator gas outlet flows can be measured with orifice meters. As separators can be less than 100% efficient these orifice meters can encounter wet gas. Therefore, in order to compare the separator outlet flow measurements with multiphase flow meters it may be necessary to know if the orifice meter is encountering wet gas, and if so, to correct the liquid induced gas flow rate prediction error. A second reason an orifice meters multiphase wet gas flow performance is important is that gas processing terminals often monitor for wet gas flow at the station orifice meters. Natural gas terminals can benefit from the orifice plate meter having an internal ability to monitor for wet gas flow, and if detected, having an available correction factor (while efforts are made to ensure the inlet flow is single phase gas flow). A third reason the wet gas performance of orifice meters is important is that many smaller well flows cannot economically justify the use of complex multiphase wet gas meters. Typically, small wet gas field producers can only economically justify single phase meters such as orifice meters. Each individual well needs a dedicated flow meter. A large collection of small wet gas producing wells with orifice meters can have a combined monetary flow similar to a single large scale multiphase flow production well. A fourth reason why orifice meter multiphase wet gas performance is of interest is that other single phase gas meter manufacturers are aiming to develop their meters to improve upon the use of orifice meters with multiphase wet gas flow. Therefore, in order to promote fair technical comparisons between an orifice meter and any other meter design it is necessary to quantify the orifice meter multiphase wet gas flow performance. Although perhaps not as obviously important as the study of multiphase and wet gas meter technologies, the study of orifice meter response to multiphase wet gas flow has significant importance.

In 2008 it was shown by the authors [1] that for natural gas with light hydrocarbon liquid (HCL) flows, 2" through 4" orifice meters with a beta ratio range of 0.25 to 0.68 had a very repeatable and reproducible wet gas flow response. The orifice meter has a smaller gas flow over-reading than Venturi and cone meters. An orifice meter gas / HCL wet gas correlation was offered [1] for the tested range, which for a known liquid flow rate gave the gas flow rate to within 2% uncertainty at 95% confidence.

Recently more data has become available, including larger meter sizes and data from natural gas with water flows and multiphase wet gas (i.e. natural gas, water **and** HCL) flows. These new data show that the existing orifice meter correlation is repeatable and reproducible across its data range. It has been found that the orifice meter wet gas response is affected by liquid properties. For all other parameters held constant, a wet gas flow with water content has a smaller liquid induced gas flow prediction error (or “over-reading”) than a wet gas flow with HCL only. It has been found that the relationship between the over-reading and the mass Water Liquid Ratio (WLR_m) is almost linear. A new orifice meter correlation is presented that includes the WLR_m term. This new correlation predicts the gas flow rate to within 2% uncertainty at 95% confidence. Finally, new CEESI 8”, 0.69 beta ratio orifice meter multiphase wet gas flow data from is presented.

2. The Definition of Wet Gas Flow Parameters

A wet gas flow is defined here to be 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. That is, the liquid can be a HCL, water or a mix of HCL and water.

The Lockhart-Martinelli parameter (equation 1) indicates the relative amount of total liquid with the gas flow. Note that \dot{m}_g & \dot{m}_l are the gas and liquid mass flow rates respectively (where \dot{m}_l is the sum of the liquid component flow), and ρ_g & ρ_l are the gas and liquid densities respectively.

$$X_{LM} = \frac{\dot{m}_l}{\dot{m}_g} \sqrt{\frac{\rho_g}{\rho_l}} = \frac{Fr_l}{Fr_g} \quad \text{--- (1)}$$

The gas to liquid density ratio ($DR = \rho_g / \rho_l$) is a non-dimensional expression of pressure. The gas and liquid densiometric Froude numbers (Fr_g and Fr_l), shown as equation 2 and equation 2a respectively, are non-dimensional expressions of the gas and liquid flow rates respectively. Note that equations 3 and 3a show the superficial gas and liquid velocities (U_{sg} and U_{sl}). Note that g is the gravitational constant, D is the meter inlet diameter and A is the meter inlet cross sectional area.

$$Fr_g = \frac{U_{sg}}{\sqrt{gD}} \sqrt{\frac{\rho_g}{\rho_l - \rho_g}} \quad \text{---- (2)} \quad \text{and} \quad U_{sg} = \frac{\dot{m}_g}{\rho_g A} \quad \text{--- (3)}$$

$$Fr_l = \frac{U_{sl}}{\sqrt{gD}} \sqrt{\frac{\rho_g}{\rho_l - \rho_g}} \quad \text{---- (2a)} \quad \text{and} \quad U_{sl} = \frac{\dot{m}_l}{\rho_l A} \quad \text{--- (3a)}$$

With one single liquid component a wet gas has one liquid density. With multiphase wet gas flow there is two liquid densities (water and HCL). In this case the liquid density used to calculate the gas to liquid density ratio and the gas and liquid densiometric Froude numbers is the average liquid density.

“Water cut” is the ratio of the water to total liquid (i.e. the sum of water and HCL) volume flow rates when the fluid is at **standard** conditions. In this paper “mass Water Liquid 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 therefore analogous to thermodynamic quality denoted as “ x ” and shown as equation 4. The WLR_m is shown as equation 5, where \dot{m}_w is the water mass flow rate and \dot{m}_{hcl} is the HCL mass flow rate.

$$x = \frac{\dot{m}_g}{\dot{m}_g + \dot{m}_l} \quad \text{--- (4)} \quad \quad WLR_m = \frac{\dot{m}_w}{\dot{m}_w + \dot{m}_{hcl}} \quad \text{--- (5)}$$

The average density of a two component liquid mixture is the total combined liquid mass per unit volume occupied by the liquid phase. It is assumed that the two liquid components are homogenously mixed. The density of this homogenous liquid phase ($\rho_{l,hom}$) is calculated by equation 6. Note that ρ_w & ρ_{hl} are the water and HCL densities¹ respectively. For multiphase wet gas flows it is this liquid mixture density that is used to calculate the wet gas flow parameters.

$$\rho_{l,hom} = \frac{\rho_w \rho_{hl}}{(\rho_{hl} WLR_m) + \rho_w (1 - WLR_m)} \quad \text{--- (6)}$$

Equation 7 shows the orifice meter single phase gas mass flow equation, where E is the velocity of approach (i.e. a geometric constant), A_t is the throat area (i.e. a geometric constant), C_d is the discharge coefficient, ε is the expansibility factor and ΔP_g is the differential pressure (DP) read due to the gas flow. Most wet gas flow conditions metered by an orifice meter produce a positive bias in the gas flow rate prediction. This is often called an “over-reading” and denoted as “OR”. When the flow is of wet gas the differential pressure read (ΔP_{tp}) is different to that which would have been read if that quantity of gas flowed alone (ΔP_g). The result is an erroneous, or “apparent”, gas mass flow rate prediction, $\dot{m}_{g,apparent}$ (see Equation 7a).

$$\dot{m}_g = EA_t C_d \varepsilon \sqrt{2 \rho_g \Delta P_g} \quad \text{--- (7)} \quad \quad \dot{m}_{g,apparent} = EA_t \varepsilon_{tp} C_{d,tp} \sqrt{2 \rho_g \Delta P_{tp}} \quad \text{--- (7a)}$$

$$OR = \frac{\dot{m}_{g,Apparent}}{\dot{m}_g} = \frac{\varepsilon_{tp} C_{d,tp}}{\varepsilon C_d} \sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} \cong \sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} \quad \text{--- (8)}$$

$$OR\% = \left(\frac{\dot{m}_{g,Apparent}}{\dot{m}_g} - 1 \right) * 100\% \cong \left(\sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} - 1 \right) * 100\% \quad \text{--- (8a)}$$

Note that $\dot{m}_{g,apparent}$, ε_{tp} and $C_{d,tp}$ are the apparent (incorrect) gas mass flow rate prediction, the gas expansibility and the discharge coefficient found respectively when applying the wet gas differential pressure. (Note that $C_{d,tp} \varepsilon_{tp} \approx C_d \varepsilon$.) Correction of this over-reading is the basis for orifice meter wet gas correlations. The over-reading

¹ The authors consider wet gas flow fluid properties to be information supplied to the flow computer from external means. Fluid property information is assumed to be correct. Whereas this is standard practice when discussing single phase flow meter performance, with wet gas flows, it is recognized that the supply of accurate fluid properties in field applications is a difficult challenge for operators.

is expressed either as a ratio (equation 8) or percentage (equation 8a) comparison of the apparent to actual gas mass flow rate.

3. Flow Patterns

The liquid dispersion in a wet gas flow depends on the flow conditions. A flow pattern is a description of the liquid dispersion. Flow patterns significantly affect the orifice meters response to wet gas flow. Figure 1 shows a 1997 Shell approximate flow pattern map for horizontal natural gas and HCL flow in a 4 inch pipe. As flow conditions change gradually one flow pattern gradually changes to another flow pattern. Therefore, the flow pattern boundaries drawn on flow pattern maps represent the approximate centre of transition zones. Many real production horizontal wet gas flows are in such transition zones.

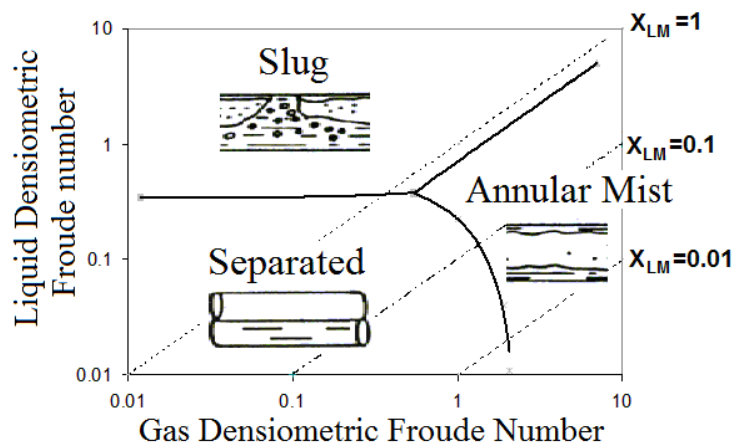


Fig 1. The Shell flow pattern map with sketches of flow patterns



Fig 2a. Gas/HCL stratified. Fig 2b. Gas/HCL transition. Fig 2c. Gas/HCL annular.

The liquid phase dispersion is dependent on the balance of forces acting upon it. The liquid in a horizontal wet gas flow is driven downstream by the gas flow. As the line pressure and / or the gas flow rate increase the energy available to drive the liquid increases. That is, as the gas densimetric Froude number increases the driving force on the liquid increases. At low gas densimetric Froude numbers the weight of the liquid dominates and the liquid will flow at the base of the pipe driven by interfacial shear stresses applied by the gas flowing across the surface of the liquid. This is called *stratified* (or *separated* flow). This flow pattern is shown in Figure 2a for the case of gas with HCL only. At higher Lockhart-Martinelli parameter values for set gas densimetric Froude numbers stratified flow can be unstable and resulting waves can periodically block the pipe. This is called *slug* flow. As the gas densimetric Froude number increases for any set Lockhart-Martinelli parameter the liquid will be forced to flow along a thin layer on the periphery of the pipe while small droplets are entrained through out the gas which flows in a central core. This is called *annular* or *annular mist* flow. As the flow pattern changes from stratified to annular mist flow it

is usually called transitional flow, as shown in Figure 2b for the case of gas with HCL only. Figure 2c shows annular mist flow for the case of gas with HCL only. As the gas densiometric Froude number increases yet further for all other conditions held constant, the amount of liquid entrainment increases, the average droplet size reduces and the thickness of the liquid annular ring reduces. Eventually, at a large enough gas densiometric Froude numbers, the ring is little more than a wetted wall and the liquid is effectively atomized with extremely small droplet diameters. This is called *homogeneous* flow (not shown in Figure 1 – but to the right side of the annular mist flow), since the flow is effectively a pseudo-single phase flow. Here, the phases are very well mixed.

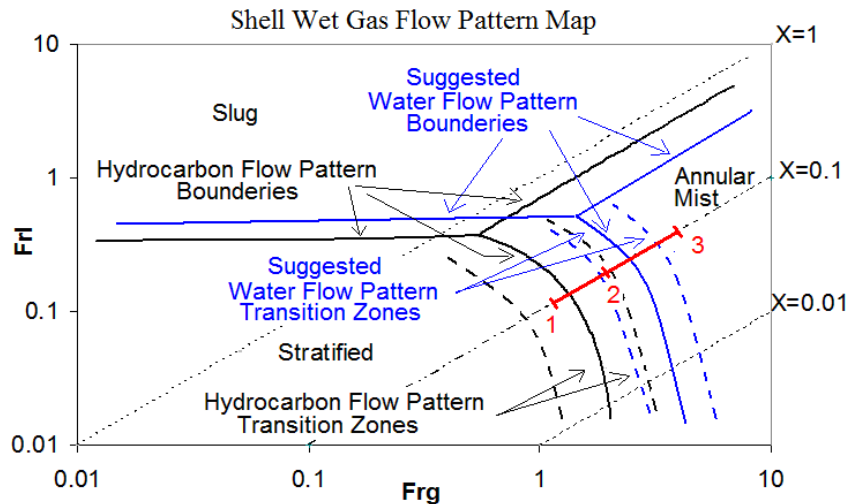


Fig. 3 Flow pattern map for gas / HCL with suggested boundaries for HCL/ water.

Figure 1 is for 4" horizontal pipe with gas and HCL. Flow patterns are affected by liquid properties (i.e. viscosity and surface tension values) and it is debated what affect pipe diameter has. It is generally agreed that as the surface tension increases a higher gas densiometric Froude number is required to change a stratified flow to annular mist flow, or an annular mist flow to a homogenous flow. Figure 3 shows a graph from Steven [2] that discusses the potential affect of plotting gas / water only data on a gas / HCL flow pattern map. The flow pattern boundaries are shifted. An increasing gas densiometric Froude number along the line of constant Lockhart-Martinelli parameter of 0.1 is shown. Three wet gas flow cases are considered, cases 1 to 3 at gas densiometric Froude numbers of 1.2, 2.5 & 5 respectively. Case 1 shows that for both gas with HCL flow only and gas with water flow only the flow pattern is stratified flow. Case 2 shows that for gas with HCL only the flow pattern is now annular mist flow, whereas with gas with water only the flow pattern is still stratified flow. Here, for otherwise identical flow conditions the liquid properties are dictating different flow patterns. Case 3 shows that for the gas with HCL flow only the flow pattern is deep into the annular mist flow pattern. The gas with water only flow pattern is also annular mist flow, but not so deep into this flow pattern region. Therefore, with case 3 the gas and HCL flow will have a smaller annular ring, more liquid entrained in the gas core and smaller average diameter droplets than the gas with water flow. For the same flow condition the gas with HCL is closer to the homogenous flow pattern than the gas with water only flow. However, as the gas densiometric Froude number continues to increase both these wet gas flows will tend to the extreme annular mist condition of homogenous flow, where the annular ring effectively disappears and the liquid droplets are atomized. Here, at this extreme

condition, the gas with HCL flow and the gas with water flow will return to having the same wet gas flow pattern, i.e. homogenous flow.



Fig4a. Gas/Water Stratified. Fig4b Multiphase transitional. Fig4c. Multiphase annular.

The above discussion discusses gas with HCL **or** gas with water flows only. However, a common production flow is gas with HCL **and** water. There are no flow pattern maps for multiphase wet gas flows. However, using the CEESI multiphase wet gas loop view port it has been observed that flow patterns of gas with HCL or water flow only are largely similar to each other even if the transition boundaries are at slightly different flow conditions. It has also been observed that the general flow patterns of multiphase wet gas flows (i.e. gas with water and HCL flows) are similar to the cases of gas with a single liquid component. However, there are slight differences such as the ability of water to carry gas bubbles in stratified flow. This has not been observed for gas with HCL (i.e. compare Figures 4a & 2a). In the transition zone between stratified and annular mist flow, multiphase wet gas flow can act slightly differently to gas with a single liquid component. The water tends to stick to the wall and runs in streaks along the wall (i.e. compare Figures 4b & 2b). At very high gas densimetric Froude numbers multiphase wet gas flow looks like annular mist / homogenous flow just like the gas with single liquid component flows (compare Figures 4c & 2c). Therefore, the CEESI multiphase wet gas flow videos show that the multiphase wet gas flow patterns are *generally* similar to the gas with single liquid component wet gas flow patterns. However, as will be seen in section 5 these slight differences are enough to require that an orifice meter wet gas correlation accounts for them.

Flow Pattern Aside 1:

Slug flow is not the same phenomenon as “severe slugging”. Slug flow is an intermittent flow pattern caused by the gas flow not having enough energy to steadily drive the liquid phase. This causes the liquid phase to periodically accelerate and decelerate thereby causing waves in horizontal flow. Depending on the size and speed of these waves they may or may not damage pipeline components such as orifice meters. However, severe slugging can be caused by liquid flooding during shut down or liquid gathering at a low point in the pipe work. The resulting liquid plug causes a pressure build up upstream which subsequently drives the relatively large liquid column downstream at high speed. Such liquid “slugs” can damage pipe line

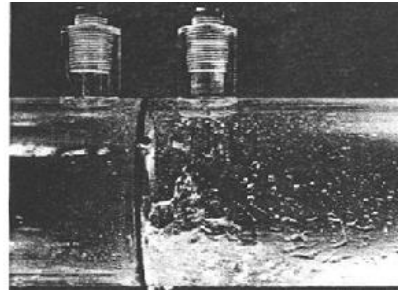
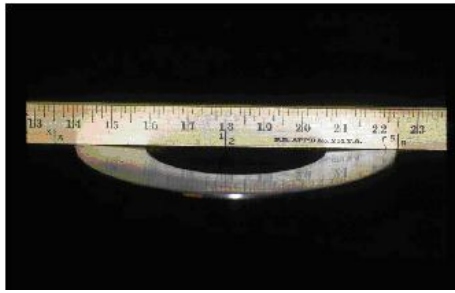


Fig 5. Plate damaged by severe slugging Fig 6. Wet gas flow through an orifice plate

components such as orifice plates (as shown in Figure 5). Orifice meters should not be used in applications where severe slugging (or other adverse conditions that can damage the plate) are probable occurrences, unless the operator accepts that regular inspection and replacement of the plate is necessary. Therefore, this paper is aimed at top-side and shore based installed orifice meters. The authors are not suggesting orifice meters should or could be used in very remote or subsea applications.

Flow Pattern Aside 2:

Videos of wet gas flow through orifice meters have long suggested that liquid gets trapped in the re-circulation zone behind the plate. Figure 6 reproduces a photograph of air and water flowing through an orifice meter (shown by Ifft at the North Sea Flow Measurement Workshop in 1997). For the light liquid loading note that very little liquid can be seen upstream. Even with a steady continuous wet gas flow arriving at the plate the liquid is **not** damming up in front of the plate. However, on the plate's downstream side liquid is clearly trapped in the recirculation zone. The low pressure tap can be seen at top dead centre at this region. There may be the perception that the DP read by an orifice meter operating in wet gas flow is not steady due to the trapped liquid and hence not reliable. However, this is only a perception. Whereas, the presence of trapped liquid downstream of the plate looks like it will cause DP measurement problems the actual data shows this is not the case. The standard deviation of any given DP from an orifice meter with wet gas is usually higher than if that meter read that value of DP with dry gas flow. However, any given DP an orifice meter produces with wet gas flow still averages over a short period of logging time to a repeatable and reproducible value.

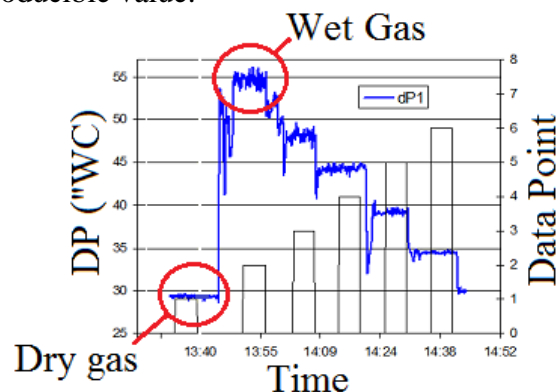


Fig 7. CEESI wet gas flow test data for a 4", 0.5 beta ratio orifice meter.

Figure 7 shows a CEESI 4", 0.5 beta ratio orifice meter wet gas flow test data. The graph axes are time vs. DP. Six stable liquid loadings data points are shown. Data point 1 was taken for dry gas flow. Note the flatness / low standard deviation of the

dry gas DP averaging approximately 29"WC over the logging period, circled as dry gas. The second point logged was a Lockhart-Martinelli parameter of 0.25. Note the significant variation / high standard deviation of the wet gas DP averaging approximately 54.5"WC over the data logging period, circled as wet gas. (Note that the over-reading here, as calculated by equation 8, is $(54.5/29)^{0.5} \approx 1.37$, i.e. 37%.) This significant increase in the DP's standard deviation is due to the wet gas flow being naturally less stable than single phase flow. However, the crucial point is that **in practical terms it does not matter**. Even with the high standard deviation, logging the DP for a relatively short period of time (in the order of a few seconds) still gives a repeatable and reproducible averaged DP value. The stability of an orifice meters DP with wet gas flow is not a problem.

Flow Pattern Aside 3:

There is some perception that orifice meters can not be used as wet gas meters as the plate "dams" the liquid. It may be true that at some horizontal wet gas flow conditions the plate can dam **some** of the liquid at some liquid depth. However, the follow-on common assumption that this means the orifice meter can not be a good wet gas meter is false. If a wet gas flow condition does cause the liquid flow to start to dam up in front of the plate, the plate can not **continually** increase the amount of liquid dammed up in front of it. At some depth of damming the wet gas flow has such a reduced cross sectional area that the gas velocity has increased to the point where an equilibrium between liquid dam depth and local gas velocity is reached. That is, the increased blockage means an increased gas velocity and increased driving force to move the liquid through the orifice. Therefore, a balance is very quickly reached for any wet gas flow condition where **if** the plate dams the liquid phase, the liquid depth and the gas velocity settle in a very short period of time during start up such that the subsequent entire mass flow rate of on coming gas and liquid flow moves through the orifice.

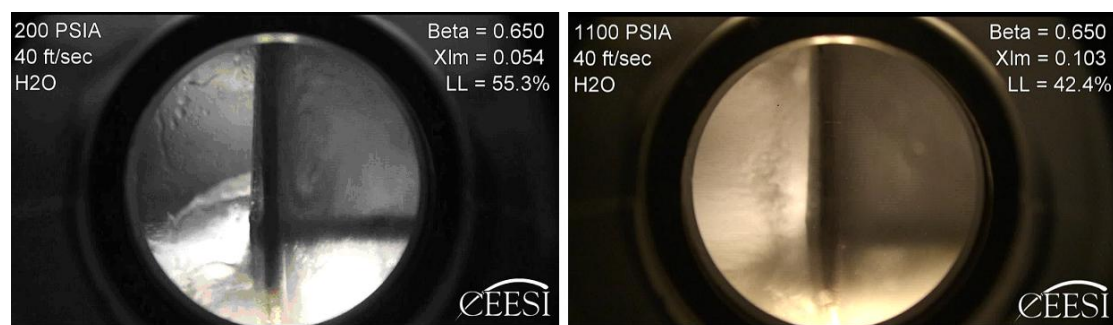


Fig 8a.Stratified flow approaching plate Fig 8b.Annular Mist flow approaching plate

Figures 8a & 8b show examples of CEESI placing a 4", 0.65 beta ratio orifice plate at a view port while flowing stratified and annular mist wet gas flow respectively. Flow is left to right. (The horizontal bar downstream of the plate is holding the plate in place. Care was taken to assure no leakage occurred around the plate.) Figure 8a shows a stratified flow approaching the plate at a Lockhart-Martinelli parameter of 0.054. The flow was steady for 20 minutes and the liquid build up in front of the plate never changed. Figure 8b shows an annular mist flow approaching the plate at a Lockhart-Martinelli parameter of 0.103. Figure 8b still shows a slight gravitational effect at the inlet with more liquid at the base of the pipe. It is interesting to note the liquid ridge approximately 1/4" upstream of the plate. This appears to be evidence of

the liquid meeting the recirculation zone upstream of the plate. Again, the flow was steady for 20 minutes and the liquid build up in front of the plate never changed.

Figures 8a & 8b confirm that liquid gets held up in the downstream re-circulation zone. However, the level of liquid entrained in the downstream re-circulation zone did not visibly change over time. The system immediately settled to that condition on start up. Therefore, any effect of any steady limited local dam in front of the plate, or liquid entrained in the orifice re-circulation zones is fully accounted for in wet gas correlations derived from the test data. Therefore, liquid damming, or liquid “hold-up”, is not a problem when using orifice meters with wet gas flow.

Flow Pattern Aside 4:



Fig 9. Wet gas flow test of an orifice meter with pressure taps at top dead centre.

When metering wet natural gas flow with a horizontally installed orifice meter it is good practice to align the pressure taps with top dead centre of the flow line. A common **dry gas** orifice meter installation is for the taps to be placed at the 3 or 9 o'clock position. However, with wet gas flow such an installation increases the chances of liquid becoming trapped in the impulse lines thereby adversely affecting the DP reading. The positioning of the taps at the top of the line minimizes the likelihood of trapped liquid in the impulse lines and maximizes the chance of drainage. It is also good practice to avoid any low / horizontal legs in the impulse lines where liquids could be trapped. Figure 9 shows an orifice meter set up for wet gas flow metering. The modern (i.e. 1990's onwards) orifice meter wet gas data generally comes from flange pressure taps orientated at top dead centre. Some earlier wet gas flow orifice meter data used by Murdock and Chisholm is not traceable. Therefore, for that early data it is not known what pressure tapping type (i.e. corner taps, flange taps etc) were used and where the taps were orientated relative to top dead centre.

4. A History of Orifice Meter & Generic DP Meter Wet Gas Flow Research

The orifice meter has been extensively used since Weymouth disclosed the meter design in 1912. Today the orifice meter is one of the most widely used meters with wet gas flows. There are two reasons for this. First, orifice meters are deliberately used with wet gas flow when financial restraints prohibit the use of more sophisticated wet gas flow meters. That is, it is often considered better to have a relatively inexpensive meter giving some flow information than to have no meter and no flow information. Secondly, orifice meters are often installed in applications where it was not originally known that the flow would be wet gas flow.

The early attempts to meter wet gas flow made the unproven assumption that the phases were always perfectly mixed, there was no slip (i.e. no difference in the gas and liquid phase velocities) and that the fluid could be modelled as a pseudo-single phase flow. That is, it was assumed that a homogenous mix of phases existed and the flow was effectively a single phase flow with averaged fluid properties. This homogenous model, expressed in modern terminology, is shown as equation set 9 & 10. A derivation of the homogenous model is given by Steven [2]. The parameters “C” & “n” are called the Chisholm parameter and Chisholm exponent respectively. The homogenous model is independent of the type of DP meter and the homogenous model over-reading is only dependent on Lockhart Martinelli parameter and gas to liquid density ratio. The homogenous model predicts that as the gas to liquid density ratio increases for a set Lockhart Martinelli parameter the over-reading reduces. Figure 10 shows sample theoretical homogenous model plots on a “Murdock Plot” (i.e. Lockhart Martinelli parameter vs. % Over-Reading).

$$m_g = \frac{\dot{m}_{g,apparent}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \quad \text{--- (9)} \quad C = \left(\frac{\rho_g}{\rho_l} \right)^n + \left(\frac{\rho_l}{\rho_g} \right)^n \quad \text{--- (10)} \quad \text{where } n = 1/2$$

In 1959 Schuster released [3] wet natural gas flow orifice meter field data that indicated that the homogenous model did not accurately describe orifice meter wet gas flow performance across all wet gas flow conditions. In 1962 Murdock [4] developed an orifice meter two-phase flow model based on the assumption of a separated flow pattern only. Most of the Murdock data set was for wet gas flows. Examination of the data set range suggests that although Murdock modelled separated flow some of his data may have had other flow patterns. Nevertheless Murdock fitted all available data, regardless of the actual flow pattern, to his separated flow model. Using modern terminology here, Murdock showed that as the Lockhart Martinelli parameter increased the over-reading increased. Figure 11 shows a sample Murdock plot for a 4”, 0.68 beta ratio orifice meter with a set gas to liquid density ratio and set gas densimetric Froude number.

Between 1967-1977 Chisholm [5, 6] continued orifice meter two-phase flow research. Chisholm, like Murdock, created a model based on the assumption of separated flow. However, Chisholm linked the over-reading to the Lockhart Martinelli parameter **and** the slip between the gas & liquid phases. Chisholm developed his model to indicate that slip was only dependent on the gas to liquid density ratio. Hence, the Chisholm equation for orifice meters states that the over-reading is dependent on the Lockhart Martinelli parameter and the gas to liquid density ratio. The homogenous equation was deliberately shown here in the same form as the Chisholm equation. Therefore, the Chisholm equation is the same form as the homogenous model, equations 9 & 10, however whereas the homogenous model has a Chisholm exponent set by theory to $n=1/2$, the Chisholm equation has the Chisholm exponent set by data fitting to $n=1/4$.

$$m_g = \frac{\dot{m}_{g,apparent}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \quad \text{--- (9)} \quad C = \left(\frac{\rho_g}{\rho_l} \right)^n + \left(\frac{\rho_l}{\rho_g} \right)^n \quad \text{--- (10)} \quad \text{where } n = 1/4$$

Therefore, Chisholm confirmed Murdock’s statement that for all other wet gas flow parameters remaining constant, as the Lockhart Martinelli parameter increased the

over-reading increased. However, Chisholm also showed that as the gas to liquid density ratio increased the over-reading reduced (as shown with sample data in Figure 12). By stating that the wet gas over-reading was dependent on slip, Chisholm was effectively stating that the flow pattern influenced the over-reading.

Between 1977 and 1997 there was only a small amount of research publicly released on wet gas flow metering with differential pressure meters. However, by the mid 1990's rising interest in wet natural gas flow metering had led to renewed interest in the work of Chisholm. Nevertheless, from the start of this more modern research the hydrocarbon production industry immediately concentrated on Venturi and cone meters rather than the earlier research on orifice meters.

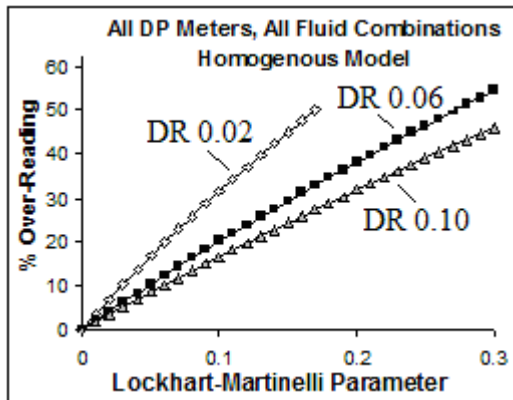


Fig 10. The Homogenous Model.

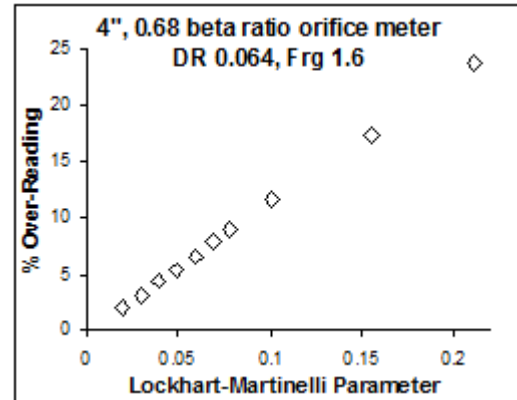


Fig 11. The liquid loading effect.

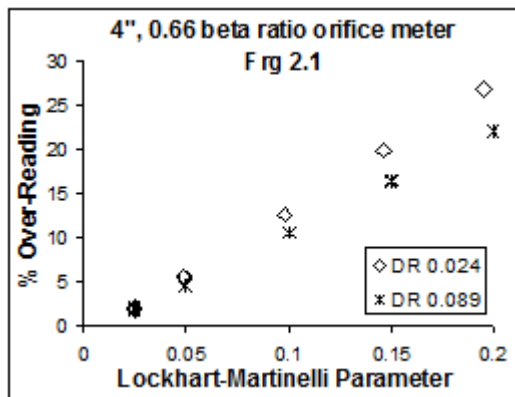


Fig 12. Gas to Liquid Density Ratio.

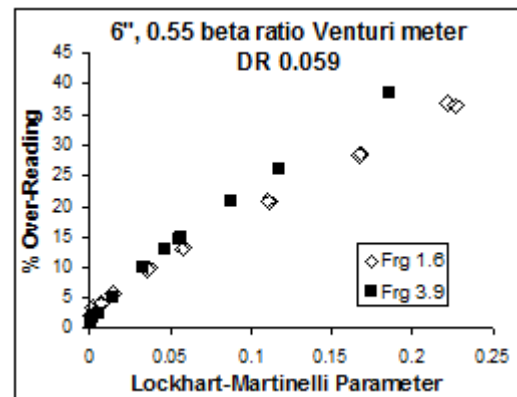


Fig 13. Gas Densiometric Froude Number.

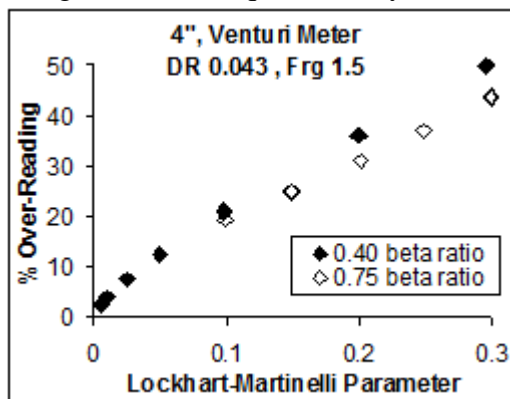


Fig 14. The beta ratio effect.

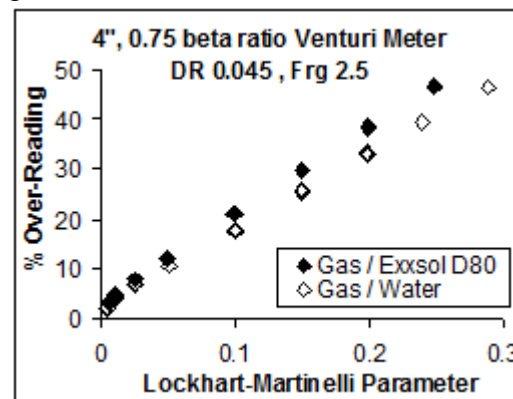


Fig 15. Fluid properties effect.

In 1997 De Leeuw [7] released wet gas flow research on a 4", 0.4 beta ratio Venturi meter where it was shown that Venturi meters, like orifice meters, had a wet gas over-

reading related to Lockhart Martinelli parameter and the gas to liquid density ratio. However, de Leeuw then showed that the flow pattern dictated the Venturi meter over-reading. De Leeuw suggested that for otherwise set wet gas flow conditions, the gas densimetric Froude number affected the flow pattern (see Figure 1), and hence the over-reading. Figure 13 shows some typical de Leeuw results for Venturi meters. For all other parameters being equal as the gas densimetric Froude number increased the over-reading increased. De Leeuw maintained the Chisholm equation form but instead of data fitting a constant Chisholm exponent (as done by Chisholm) de Leeuw linked the Chisholm exponent to the gas densimetric Froude number. This accounted for the effect of the flow pattern. De Leeuw indicated that for the liquid loading range of a wet gas flow a stratified flow could be reasonably described with a constant Chisholm exponent, whereas a wet gas annular mist flow requires a Chisholm exponent expressed as a function of gas densimetric Froude number. De Leeuw effectively suggested that for the 4", 0.4 beta ratio Venturi meter with gas with HCL, some "transitional" gas densimetric Froude number ($Fr_{g,trans}$) existed. Below this gas densimetric Froude number value a stratified flow exists and a constant Chisholm exponent is reasonable. As the gas densimetric Froude number increases above this transitional value the flow pattern transitions into annular mist flow, then on to mist flow and finally homogenous flow. Here, the Chisholm exponent is required to be a function of the gas densimetric Froude number to account for the changing flow patterns. De Leeuw set this transitional gas densimetric Froude number value for his 4", 0.4 beta ratio Venturi meter with gas and HCL only at 1.5. The de Leeuw data fit of Chisholm exponent vs. gas densimetric Froude number is reproduced here as Figure 16. The de Leeuw 4", 0.4 beta ratio Venturi meter correlation is shown as equation set 9, 10, 11a & 11b. The stated uncertainty within the de Leeuw data range was $\pm 2\%$ "with a few outliers".

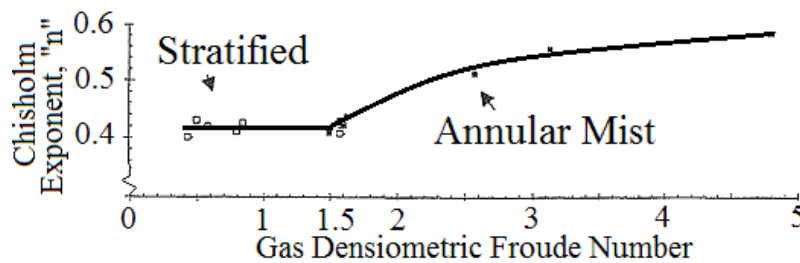


Figure 16. The de Leeuw [7] Venturi meter data fit of Chisholm Exponent vs. Fr_g.

$$m_g = \frac{\dot{m}_{g,apparent}}{\sqrt{1 + CX_{LM}^2 + X_{LM}^2}} \quad \text{--- (9)} \quad C = \left(\frac{\rho_g}{\rho_l} \right)^n + \left(\frac{\rho_l}{\rho_g} \right)^n \quad \text{--- (10)}$$

$$n = 0.41 \quad \text{for } Fr_g \leq 1.5 \quad \text{-- (11a)}$$

$$n = 0.606 \{1 - \exp\{-0.746 Fr_g\}\} \quad \text{for } Fr_g > 1.5 \quad \text{-- (11b)}$$

In 2002 & 2003 Stewart et al [8, 9] showed that for cone and Venturi meters the beta ratio influences the wet gas flow over-reading. Stewart showed that for set wet gas flow conditions, the smaller the beta ratio of a cone or Venturi meter the larger the over-reading. Figure 14 shows for the same wet gas flow conditions the smaller the Venturi meter beta ratio the larger the wet gas over-reading. This effect is seen to be significant for cones and Venturi meters. Therefore, the use of a cone or Venturi meter

wet gas correlation created for one beta ratio with a cone or Venturi meter with another beta ratio can produce significant biases in the gas flow prediction.

In 2006 Reader-Harris [10] showed that gas properties have no effect on a DP meters wet gas over-reading. In 2006 Steven [11] and Reader-Harris [10] showed that for Venturi meters the type of liquid can influence the DP meter wet gas over-reading. Figure 15 shows two wet gas flow data sets for a Venturi meter where the wet gas flow conditions are identical except one wet gas flow has water and the other a HCL. Changing liquid properties changes the Venturi meters wet gas over-reading. Water, tends to cause a lower wet gas flow over-reading than HCL. In 2006 Steven [2] suggested that the liquid property effect on Venturi wet gas flow over-reading was due to flow patterns. It was suggested that different liquid properties produce different flow patterns for otherwise set wet gas flow conditions. Steven postulated that wet gas flows with different liquid properties had different transitional gas densimetric Froude numbers for when stratified flow turned to annular mist flow (as shown in Figure 3). Steven stated that if the flow pattern of two different liquid property wet gas flows were the same then the Venturi meter over-reading would be the same. Hence, for flow conditions where the flow pattern was stratified or homogenous regardless of the liquid properties then no liquid property effect on over-reading is evident. Only in the industrially common intermediate flow conditions between separated and homogenous flow patterns is a liquid property effect on over-reading evident.

In many wet natural gas production flows the liquid is a mix of water **and** HCL. In 2008 the authors [1] produced a 4", 0.75 beta ratio cone meter gas / HCL wet gas correlation with an uncertainty of $\pm 2.6\%$. In 2009 Steven [12] showed a WLR_m effect with this meters wet gas flow performance. However, whereas the WLR_m was seen to have some effect, for this cone meter the effect was difficult to quantify. The resulting cone meter wet gas correlation treated the WLR_m effect as scatter. Therefore, the resulting gas prediction had a rather large uncertainty of $\pm 4\%$.

In 2006 Steven [2] observed that as the gas densimetric Froude number increased the wet gas flow pattern tended towards homogenous flow. Therefore, any DP meter wet gas correction should tend to the natural boundary condition of the homogenous flow model as the gas densimetric Froude number increased. Hence, whereas all DP meter wet gas correlations could be of the form of de Leeuw, when the Chisholm exponent is fitted to the gas densimetric Froude number, the value should tend to $\frac{1}{2}$ as the gas densimetric Froude number tends to infinity (i.e. $Frg \rightarrow \infty$ then $n \rightarrow \frac{1}{2}$). In 2007 Gibson [13] commented that this was idealised. In reality the pseudo single phase homogenous flow was not true single phase flow and the gas would still loose energy accelerating the liquid through a DP meters reducing area. Hence there was scope for the asymptotic value of the Chisholm exponent to be set to slightly different values than $\frac{1}{2}$. Such a scenario can be seen by de Leeuw's equation where for $Frg \rightarrow \infty$ then $n \rightarrow 0.606$. However, in the absence of any high gas densimetric Froude number data showing otherwise, it is good practice to fit the equation such that $Frg \rightarrow \infty$ then $n \rightarrow \frac{1}{2}$. Therefore, Steven proposed that DP meter wet gas correlations should be of the general form, equation set 9, 10, 12a & 12b.

$$m_g = \frac{\dot{m}_{g,apparent}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \quad \text{--- (9)} \quad C = \left(\frac{\rho_g}{\rho_l} \right)^n + \left(\frac{\rho_l}{\rho_g} \right)^n \quad \text{--- (10)}$$

$n = \text{constant}$ $n = f(Frg)$ <p style="text-align: center;">where f is some data fitted function such that $Frg \rightarrow \infty$ then $n \rightarrow 1/2$</p>	$\text{for } Frg \leq Frg_{trans} \text{-- (12a)}$ $\text{for } Frg > Frg_{trans} \text{-- (12b)}$
---	--

In 2008 Britton et al [14] discussed the effect of meter size (i.e. diameter) and orientation on a Venturi meters wet gas flow performance. The few data sets available to Britton on diameter were contradictory and did not allow a definitive statement on the effect of diameter on Venturi meter wet gas flow performance. However, Britton did show that meter orientations affects the flow pattern and therefore flow performance. Hence, wet gas correlations for Venturi meters are only valid for the meter orientation for which they were created. No wet gas flow orifice meter performance orientation effect has been publicly released. However, it is expected that orifice meters will have a similar reaction to wet gas flow orientation as Venturi meters. Therefore, it should be noted that the discussion on orifice meter wet gas performance in this paper relates solely to horizontal wet gas flows.

After Chisholm's research there was little publicly released on orifice meter wet gas flow performance for many years. However, limited private research had taken place between 1993 & 2007. In 1993 Ting [15] stated that an orifice meter can under-read at very low Lockhart-Martinelli parameters, e.g. see Figure 22. (It has been postulated that the reason is a reduced orifice meter run friction factor due to the wetted internal surface.) As the Lockhart Martinelli parameter tends to zero the "over-reading" crosses the Lockhart Martinelli parameter value marginally above zero. No orifice meter wet gas correlation accounts for this. The "under-reading" is evident for $X_{LM} < 0.01$ and is less than -2%. As DP meter wet gas correlations typically have a performance of $\pm 2\%$ they are not generally applied at $X_{LM} < 0.02$.

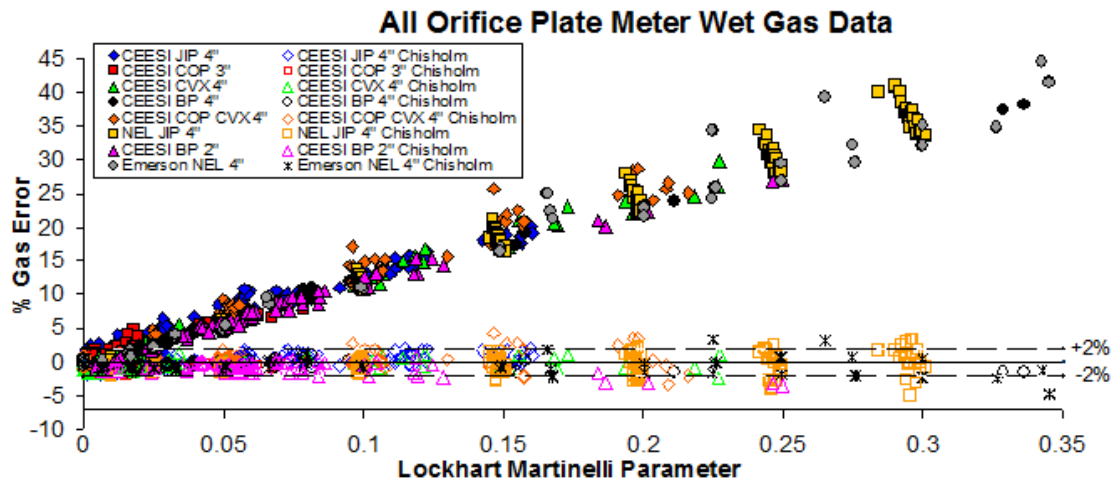


Fig 17. Orifice meter wet gas data available in 2007 with Chisholm correction.

A 1999-2002 Joint Industry Project (JIP) at CEESI tested horizontal 4" orifice meters with 0.3414, 0.4035, 0.4965 & 0.6826 beta ratios. The CEESI JIP confidentiality agreement expired in 2007. Between 2002 & 2008 ConocoPhillips (CoP), Chevron (CVX), BP and CEESI conducted private and joint orifice meter wet gas flow tests at CEESI. Furthermore, a second JIP and independently Emerson, had tested horizontal 4", 0.65 beta ratio orifice plate meters with nitrogen / exxsol D80 wet gas flow at NEL. As of 2007 all parties began pooling their data sets to allow joint analysis. Hence, in 2007 Steven et al [16] and Hall et al [17] released papers discussing

horizontal orifice meter wet gas flow performance. Steven et al [16] grouped all available orifice meter data and plotted the over-readings (see Figure 17). The data sets are shown in the Appendix Tables 1 thru 8. The diameter range was 2" to 4". The beta ratio range was 0.24 to 0.73. The fluids were mostly gas with HCL. (The only gas with water data was a very limited BP 2", 0.515 beta ratio orifice meter data set from CEESI.) These data sets confirmed that the orifice meter tends to have a lower over-reading than the Venturi and cone meters. That is, the orifice meter is less sensitive to the Lockhart Martinelli parameter than the other common DP meter designs.

In 2007 Steven applied the Chisholm correlation to the modern data. The Chisholm correlation, for a known liquid flow rate, fitted all the available data to $\pm 2\%$ to 90% confidence. However, it was noted that the Chisholm correlation did not account for any gas densimetric Froude number or beta ratio effect. Modern research with Venturi and cone meters had shown that both these parameters influenced a DP meters wet gas flow over-reading.

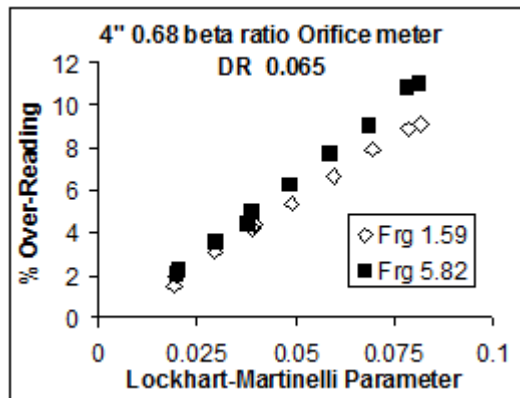


Fig 18. Gas Densimetric Froude Number.

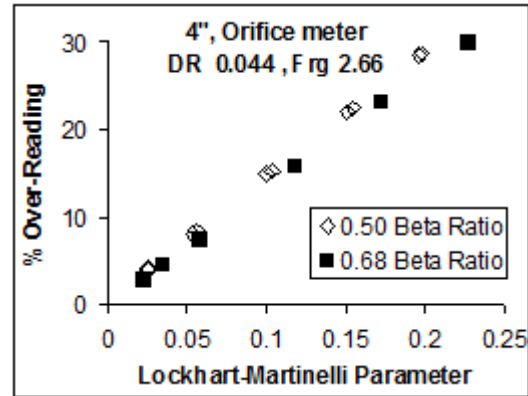


Fig 19. The beta ratio effect.

In 2007 Hall [17] showed that orifice meters with wet gas flow did exhibit a gas densimetric Froude number effect. Figure 18 shows a sample of Hall's data. As the gas densimetric Froude number increased the over-reading increased. Steven [16] showed that orifice meters with wet gas flow did exhibit a beta ratio effect. Figure 19 shows a sample of Steven's data. As the beta ratio increased the over-reading reduced. However, as found with the Lockhart Martinelli parameter, the orifice meter wet gas over-reading was found to be far less sensitive to the beta ratio than the cone and Venturi meters. Figure 19 shows that the difference between the 0.5 & 0.68 beta ratios is small. Unlike other DP meter designs, the orifice meter wet gas over-reading beta ratio effect is small enough to be practically ignored. This helps explain why earlier researchers did not mention any beta ratio effect.

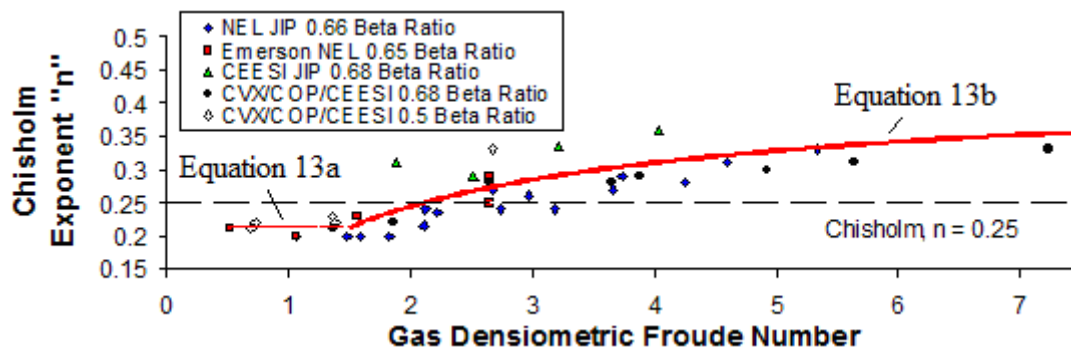


Fig 20. Hall et al [1] 2008 orifice meter data fit of Chisholm exponent to Fr_g.

In 2008 Hall et al [1] released an orifice plate wet gas flow correlation for 2" to 4" meters and any beta ratio for gas with HCL only. This equation updated Chisholm's correlation by including a gas densiometric Froude number term. Figure 20 shows the Chisholm exponent fitted to the gas densiometric Froude number for five of the then available orifice meter wet gas data sets. The remaining then available data sets were used as independent data to check the new fit, which is reproduced here as equation set 9, 10, 13a & 13b. Figure 21 shows the same uncorrected data as Figure 17, with the 2008 Hall correction factor applied. The result is a correction of the gas flow prediction for a known liquid flow rate of $\pm 2\%$ to 95% confidence. However, it was found that the 2" BP data that had a WLR_m range of $0\% \leq \text{WLR}_m \leq 100\%$ was corrected to approximately 0.5%/-3%. It was not known if the diameter, the WLR_m or both parameters caused this slight shift.

$$m_g = \frac{\dot{m}_{g, \text{apparent}}}{\sqrt{1 + CX_{LM}^2 + X_{LM}^2}} \quad \text{--- (9)} \quad C = \left(\frac{\rho_g}{\rho_l} \right)^n + \left(\frac{\rho_l}{\rho_g} \right)^n \quad \text{--- (10)}$$

$$n = 0.214 \quad \text{for } Fr_g \leq 1.5 \quad \text{--- (13a)}$$

$$n = \left(\left(\frac{1}{\sqrt{2}} \right) + \left(\frac{0.3}{\sqrt{Fr_g}} \right) \right)^2 \quad \text{for } Fr_g > 1.5 \quad \text{--- (13b)}$$

where f is a data fitted function such that $Fr_g \rightarrow \infty$ then $n \rightarrow 1/2$

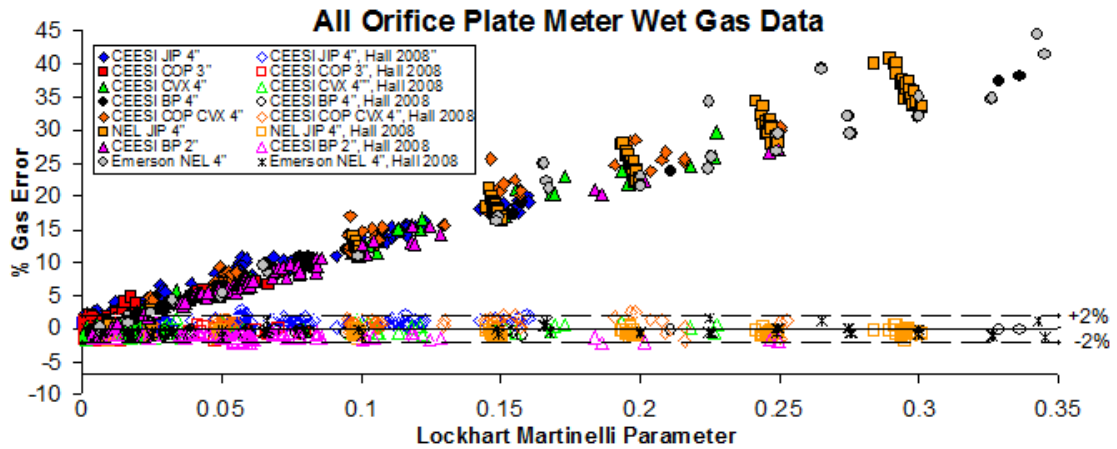


Fig 21. Orifice meter wet gas data available in 2007 with Hall 2008 correction.

5. New Orifice Meter Wet Gas Flow Research

In 2010 BP and CoP tested a 4", 0.62 beta ratio orifice meter at CEESI. This was the third multiphase (i.e. natural gas with HCL **and** water) wet gas flow orifice meter data set CEESI had recorded since the upgrade of the CEESI wet gas facility to multiphase wet gas flow in 2007. However, the earlier two data sets were recorded as extra non-commercial tests. They had not been analysed. BP (Hall) subsequently reported that their 4", 0.62 beta ratio orifice meter multiphase data (with $0\% \leq \text{WLR}_m \leq 100\%$) did not *all* agree with the 2008 orifice meter wet gas correlation. Figure 22 shows the uncorrected multiphase wet gas data and the 2008 correction. (Note the legends "WLR" in the following graphs represent the mass water liquid ratio.) Figure 22a shows only these data after correction. Clearly the data set is not corrected to $\pm 2\%$ at

95% confidence. Some of the data is over-corrected. Figure 22a shows that there is a WLR_m effect. The gas with HCL only (WLR_m 0%) data is corrected within the 2008 correction factor uncertainty. However, as the WLR_m increases clearly the 2008 correlation begins to over-correct the data.

Figure 22 indicates that the water component in the liquid phase of the wet gas flow is reducing the over-reading to a lower value than would occur if the Lockhart Martinelli parameter was from HCL alone. Furthermore, Figure 22a suggests that there is a relationship between the orifice meter wet gas flow over-reading and the WLR_m . The higher the WLR_m the lower the over-reading and therefore the larger the over-correction caused by the 2008 correction factor. This result initiated further research into orifice meter wet gas flow performance.

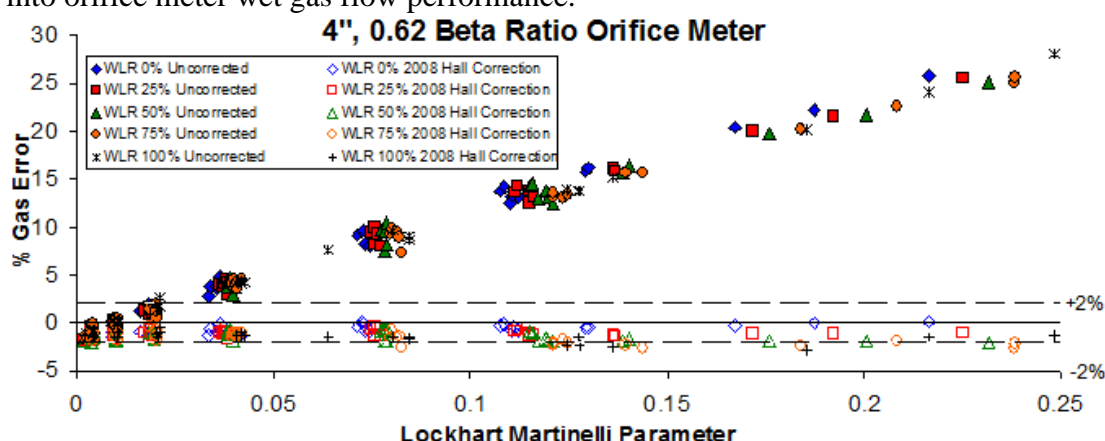


Fig 22. BP / CoP / CEESI 2010 multiphase wet gas orifice meter data.

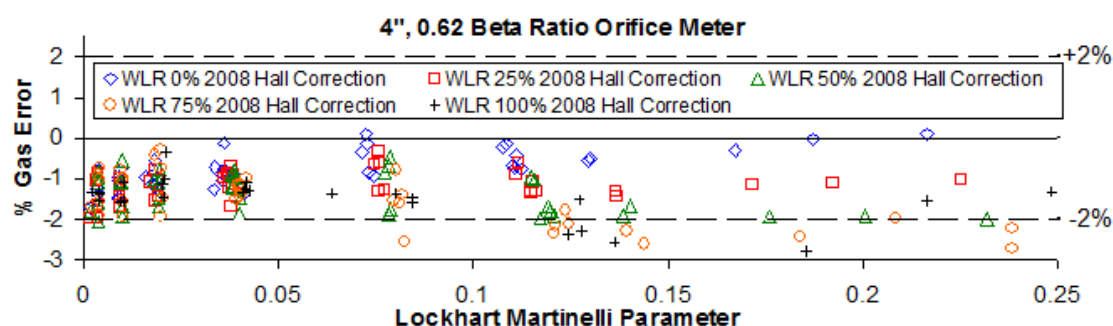


Fig 22a. BP / CoP / CEESI 2010 corrected multiphase wet gas orifice meter data.

CEESI pooled the available data sets that had not previously been used to create the 2008 correlation. One new data set for gas with HCL only was available. This was used as new check data for the existing 2008 gas with HCL correlation. The 2008 correlation was to be used as the new WLR_m inclusive correlations baseline for 0% WLR_m . Three new multiphase wet gas flow orifice meter data sets were available.

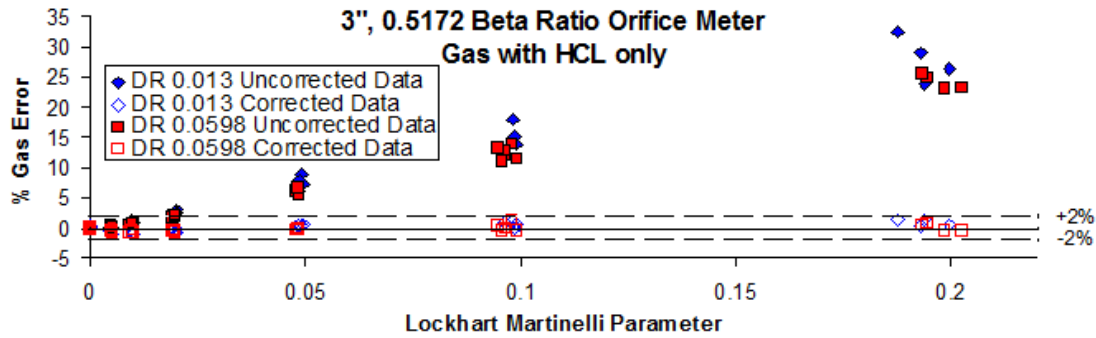


Fig 23. Sick Maihak 3", 0.517 beta ratio gas with HCL, with Hall 2008 correction.

In 2010 Sick Maihak tested at CEESI a 3", 0.517 beta ratio orifice meter with gas and HCL only. The data set was inside the 2008 orifice meter wet gas correlation stated range. However, the 3" orifice meter data set had higher Lockhart Martinelli parameters for a 3" orifice meter than the original 2008 massed data set. Therefore, using this data set to check the original correlation checks the interpolation validity of the 2008 correlation. Figure 23 shows the uncorrected and corrected data. As expected the existing correction factor corrected the data to within $\pm 2\%$ to 95% confidence. This confirms that the existing correlation correctly predicts the response of a 2" to 4" orifice meter with gas and HCL only wet gas flows.

There are four available CEESI multiphase wet gas flow orifice meter data sets. There are three separate multiphase wet gas flow data sets from the same 4", 0.62 beta ratio meter installed downstream of the commercial meter test locations. These data sets are from the 2007 commissioning of the CEESI multiphase wet gas loop, the 2010 BP / CoP multiphase meter tests and a 2010 data set from data logged while a third party tested another commercial multiphase meter upstream. The fourth data set is the previous existing BP 2", 0.515 beta ratio orifice meter multiphase wet gas data set. As the commissioning data was the most comprehensive multiphase wet gas orifice data set it was used to create the multiphase wet gas orifice meter correlation. The three other data sets are used as check data to the resulting data fit.

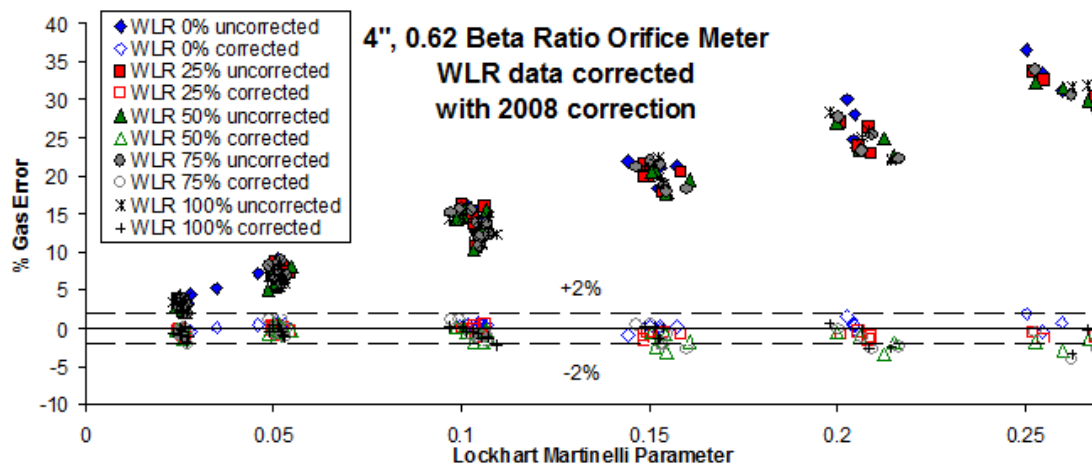


Fig 24. CEESI multiphase facility commissioning orifice meter data.

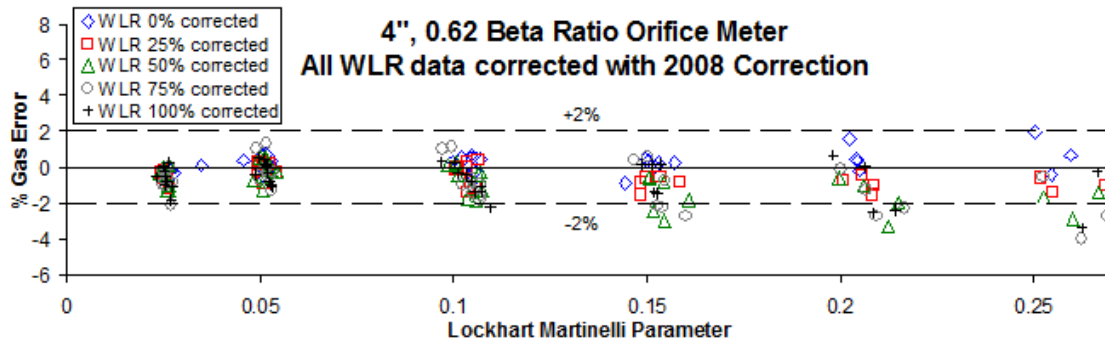


Fig 24a. CEESI multiphase facility commissioning orifice meter data, corrected.

Figure 24 shows the CEESI multiphase wet gas facility commissioning data uncorrected and corrected with the existing 2008 gas with HCL correction factor. Figure 24a highlights these correction results. As found with the BP / CoP / CEESI results (see Figure 22a) the WLR_m has an effect. From $WLR_m \geq 50\%$ some of the data is being over-corrected. This confirmed the earlier result and the requirement for a WLR_m term in an orifice meter multiphase wet gas flow correlation.

The new correlation was created by plotting Lockhart Martinelli parameter vs. over-reading for constant gas to liquid density ratio, gas densimetric Froude number and WLR_m values. For each data set and subsequent plot the Chisholm correlation model is fitted to find the particular Chisholm exponent, “n”. Figures 25a & 25b show sample plots of the massed graphs created. The resulting Chisholm exponent and gas densimetric Froude numbers are then plotted as in Figures 16 & 20. Figure 26 shows the gas with HCL data (i.e. 0% WLR_m) used to create the 2008 correlation and then

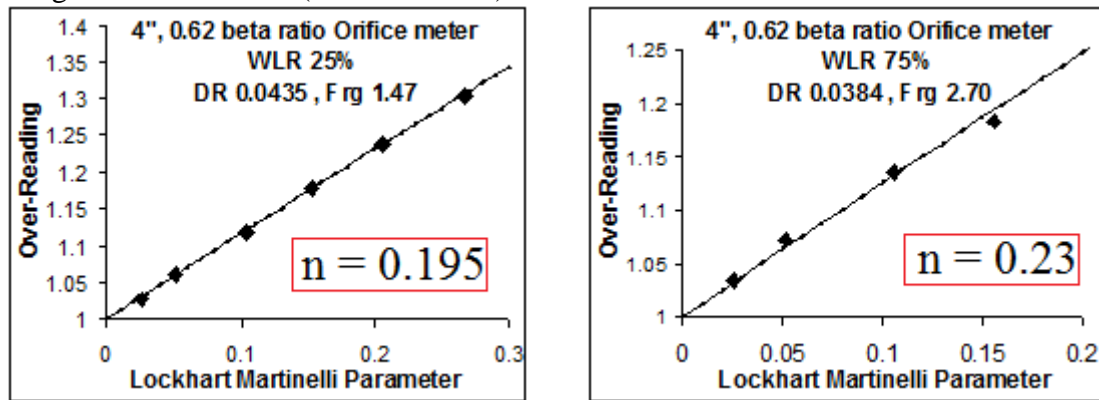


Fig 25a. Chisholm Exponent Fit, WC25%. Fig 25b. Chisholm Exponent Fit, WC75%.

the CEESI 2007 multiphase wet gas flow data for 25% WLR_m , 50% WLR_m , 75% WLR_m & 100% WLR_m . Clearly, there is a substantial amount of scatter. However, this is a common feature of such a plot. The scatter is significant even at the existing 0% WLR_m data set and the resulting 2008 correlation worked well. A pattern is generally evident amongst the scatter. Higher WLR_m values give on average lower Chisholm exponents. Therefore, a new multiphase wet gas orifice meter correlation could be fitted. The multiphase wet gas flow correlation fitted to the 4-inch, 0.62 beta ratio orifice meter is shown as equation set 9, 10, 14, 15, 16, 17a & 17b.

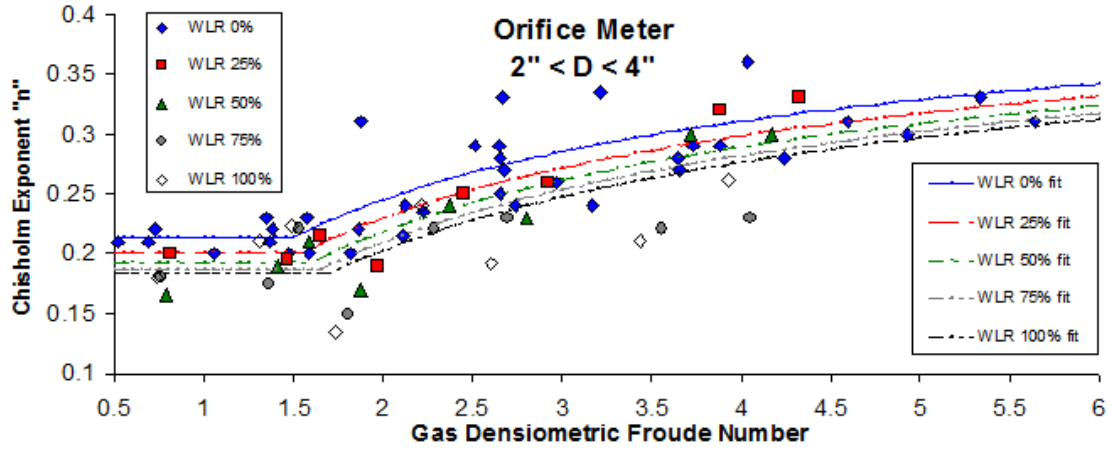


Fig 26. CEESI multiphase wet gas flow facility 4" orifice meter data.

The inclusion of the WLR_m effect has clearly made the correlation more complicated. To apply this correlation the water and HCL flow rates and the gas, water and HCL densities must be initially known. The gas flow rate prediction is found by iteration. The correlation is semi-empirical. As the WLR_m increases and the liquid changes from light HCL to water the increasing surface tension also increases the required gas densimetric Froude number to transition the flow pattern from stratified to annular mist flow (see equation 14). As the WLR_m increases for otherwise given wet gas flow conditions the flow pattern tends more towards separated flow. Hence, the larger the WLR_m , the larger the value of #A, and the lower the resulting Chisholm exponent and over-reading. Also note that the correlation is set to extrapolate such that $Fr_g \rightarrow \infty$ then $n \rightarrow 1/2$. Finally note that if this WLR_m sensitive correlation is set to 0% WLR_m , then #A is 0.3, $Fr_{g, strat}$ is 1.5 & n_{strat} is 0.214, i.e. the 2008 correlation for gas with HCL only, as required.

$$\dot{m}_g = \frac{\dot{m}_{g, apparent}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \quad \text{--- (9)} \quad C = \left(\frac{\rho_g}{\rho_l} \right)^n + \left(\frac{\rho_l}{\rho_g} \right)^n \quad \text{--- (10)}$$

$$Fr_{g, strat} = 1.5 + (0.2 * WLR_m) \quad \text{-- (14)}$$

$$\#A = 0.4 + \{-0.1 * (\exp(-WLR_m))\} \quad \text{-- (15)}$$

$$n_{strat} = \left\{ \left(\frac{1}{\sqrt{2}} \right) - \left(\frac{\#A}{\sqrt{Fr_{g, strat}}} \right) \right\}^2 \quad \text{-- (16)}$$

$$n = n_{strat} \quad \text{for } Fr_g \leq Fr_{g, strat} \quad \text{-- (17a)}$$

$$n = \left(\left(\frac{1}{\sqrt{2}} \right) - \left(\frac{\#A}{\sqrt{Fr_g}} \right) \right)^2 \quad \text{for } Fr_g > Fr_{g, strat} \quad \text{-- (17b)}$$

Note that $Fr_g \rightarrow \infty$ then $n \rightarrow 1/2$ as required

Correlation Procedure:

Step 1: Use equation 5 to give the WLR_m .

Step 2: Use equation 6 to predict the average liquid density.

Step 3: Use equation 14 to predict the gas densimetric Froude number required at a given WLR_m to cause transition between separated and annular mist flow.

Step 4: Use equation 15 to predict the correlation parameter #A, which is the variable that partially dictates the scale of the over-reading depending on the WLR_m along with the gas densimetric Froude number.

Step 5: Use equation 16 (with equations 14 & 15) to predict the constant Chisholm exponent value for a given WLR_m if separated flow is predicted.

Step 6: Iterate the gas flow rate in equation set 9, 10, 1, 2, 3, 5, 6, 17a & 17b. The iteration starting gas flow rate value is advised to be the orifice meters uncorrected gas mass flow rate prediction.

Figures 27 show the CEESI multiphase commissioning data uncorrected and corrected with the new multiphase wet gas correction factor. Figure 27a highlights these correction results. The results in Figure 27a are clearly a significant improvement on the results shown in Figure 24a. The new correlation under-corrects *a few* of the higher WLR_m data points. However, the correlation fitted all the CEESI multiphase commissioning data (188 points at $X_{LM} \geq 0.02$, $0\% \leq WLR_m \leq 100\%$) to 2% at 95% confidence, and it was found on balance, when the correlation was applied to the other multiphase data sets that the correlation was sound. Other data sets had outliers in the other direction, e.g. Figure 22b shows the BP / CoP / CEESI 4", 0.62 beta ratio orifice meter data corrected by the new correlation. Here, there are three outliers that are over-corrected. However, across the massed data of the four available data sets the correlation gave an uncertainty $\pm 2\%$ to 95% confidence. Of the 668 points in the combined multiphase wet gas flow orifice meter data sets at $0\% \leq WLR_m \leq 100\%$ and

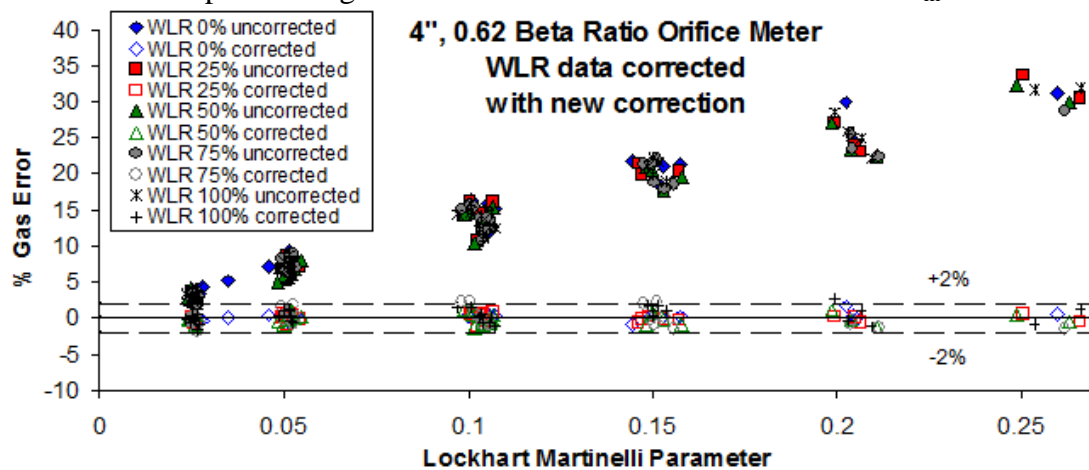


Fig 27. CEESI multiphase facility commissioning orifice meter data.

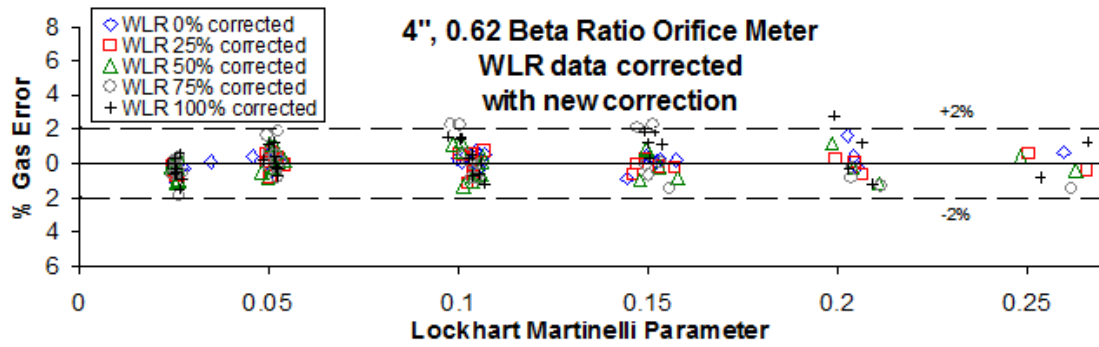


Fig 27a. CEESI multiphase facility commissioning orifice meter data, corrected.

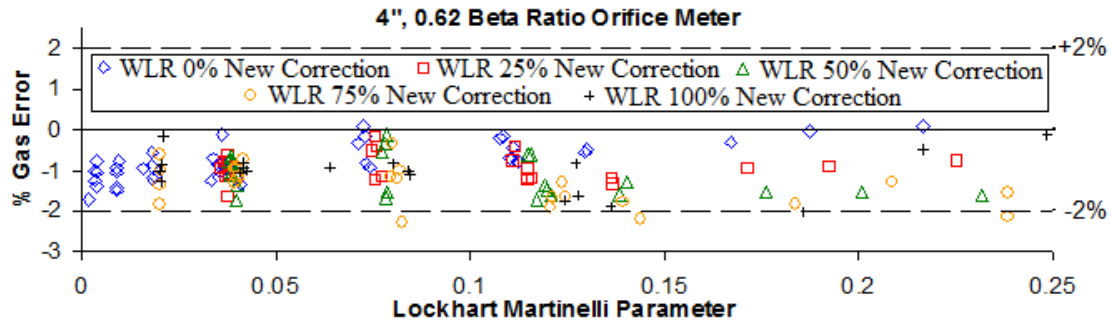


Fig 22b. BP / CoP / CEESI 2010 corrected multiphase wet gas orifice meter data.

$X_{LM} > 0$ there are 26 points with a gas flow rate prediction $>2\%$ from the reference meter. Hence, 96% of the data is corrected to within 2% uncertainty. If we remove $X_{LM} < 0.02$, which is often considered to artificially improve the statistics, there are 500 points within the range of $0\% \leq WLR_m \leq 100\%$ and $X_{LM} \geq 0.02$. Of these there are 11 points with a gas flow rate prediction $>2\%$ from the reference meter. Hence, 98% of the data is corrected to within 2% uncertainty. If we remove $X_{LM} < 0.02$ data and 0% WLR_m data (due to 0% WLR_m being covered by the 2008 correlation) the combined four multiphase wet gas orifice meter data sets have 417 points and 12 of these data points. Hence, 97% of the data is corrected to within 2% uncertainty.

Figures 28 shows all available multiphase wet gas orifice data sets uncorrected and corrected by the new correlation. Figure 28a shows the corrected data only. Many of the corrected data sets outliers lie at $X_{LM} < 0.02$. There is a debate in industry regards whether wet gas correlations should be applied to DP meters at very low Lockhart

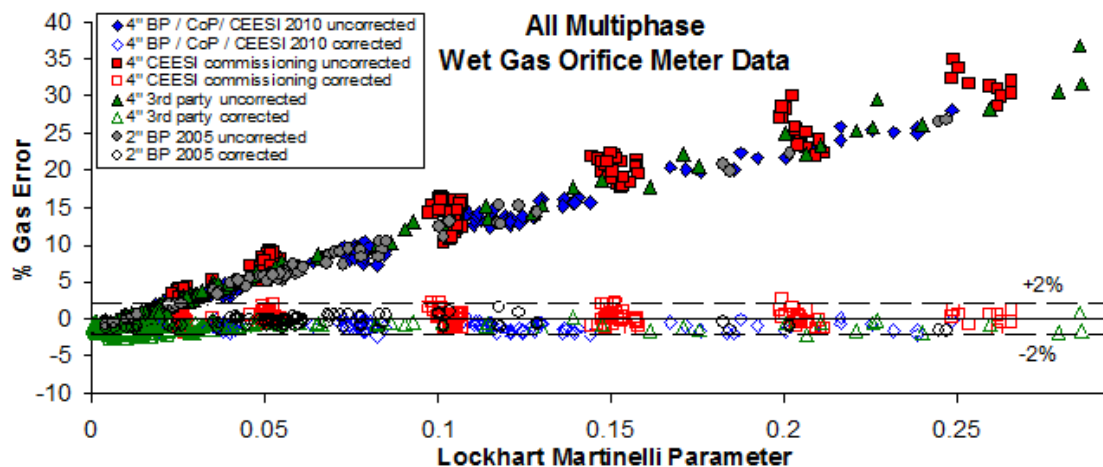


Fig 28. All CEESI multiphase wet gas flow orifice meter data sets.

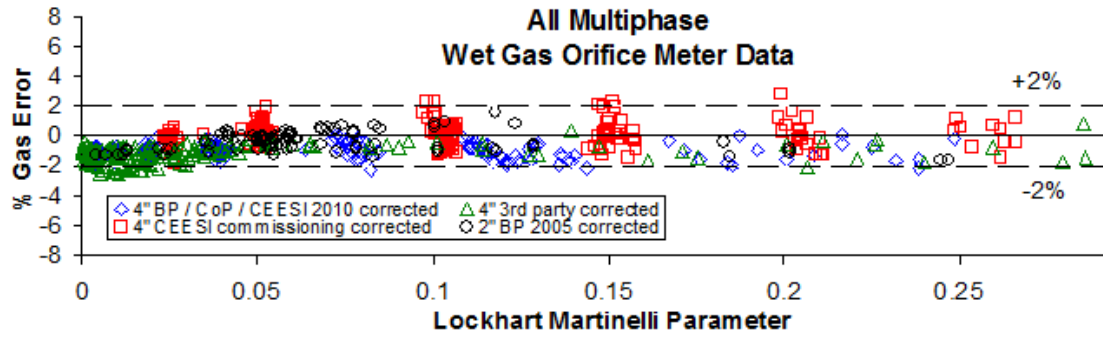


Fig 28a. All CEESI multiphase wet gas flow orifice meter data sets, new correction

Martinelli parameter values. Often the liquid induced gas flow rate error (i.e. the over-reading error) is no greater than the uncertainty induced by the correction factor of choice. This issue can be more prevalent with orifice meters with Ting's [15] finding that *very* low Lockhart Martinelli parameters can produce a *slight* under-reading. No conventional orifice meter wet gas correction (including this new correlation) accounts for this phenomenon. Hence, at very low Lockhart Martinelli parameter values this conventional wet gas correlation can exasperate the problem and further reduce the gas flow rate prediction, hence increasing the under-reading as seen at $X_{LM} < 0.02$ in Figure 28a.

It is noteworthy that with the effect of multiphase flow accounted for, all the BP 2", 0.515 beta ratio orifice meter data is now corrected to within 2%. This suggests that between 2" and 4" orifice meters at least, there is no significant diameter effect. However, it should be noted that this is a relatively small diameter difference. It is still an open question if there is a diameter effect on the orifice meter wet gas over-reading occurring across large diameter differences. This issue will be discussed further in section 8.

Figure 29 shows all available wet gas orifice meter data sets plotted together, with and without the new correction factor applied. These data consist of the existing gas with HCL data used in 2008, the new gas with HCL only data and the new multiphase wet gas flow data. In total there are 1656 wet gas points ($X_{LM} > 0$) and 36 points have a gas flow rate prediction that differs from the reference meter by greater than 2%. Hence, 98% of the data is corrected to within 2% uncertainty. Removing the low Lockhart Martinelli parameter values ($X_{LM} < 0.02$) leaves 1161 data points and of these 18

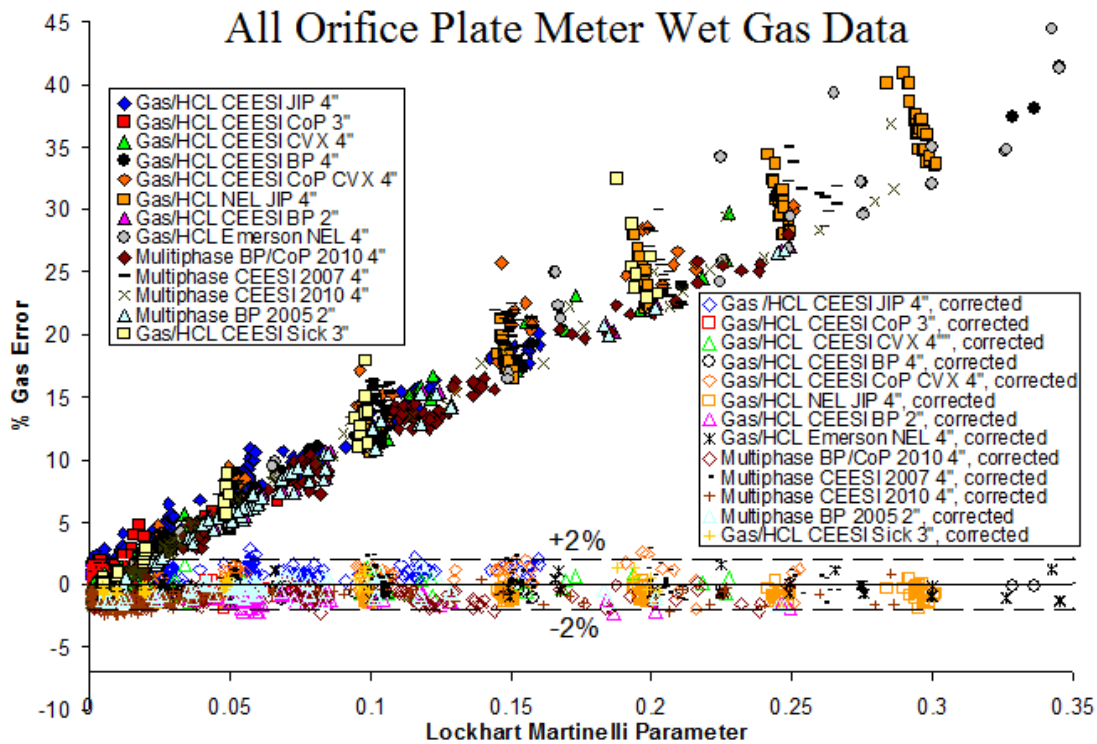


Fig 29. All 2" to 4" orifice meter wet gas data with and without new correction.

points have a gas flow rate prediction that differs from the reference meter by greater than 2%. Hence, 98% of the data is corrected to within 2% uncertainty.

Aside - Comment on the Complexity of the New Wet Gas Orifice Meter Correlation:

There is an increase in complexity between the gas with HCL only correlation and the gas with HCL **and** water correlation. This is unfortunate but cannot be helped. By adding new phenomena, i.e. liquid properties, the situation naturally becomes more complicated.

The authors wish to promote the idea of potential operators of the orifice meter multiphase wet gas flow correlation using trusted software from a reputable flow computer company. This is analogous to applying the Reader-Harris Gallagher equation for discharge coefficient. Few try and implement it from first principles, and most use known software programs. It is of course conceded that at the time of first release the flow computer companies will still have to precisely implement this correlation and rigorously assure the correctness of such implementation.

6. Monitoring the Liquid Loading of Wet Gas Flow Through an Orifice Meter

A limitation to the use of a gas meter with a wet gas correlation to meter wet gas flow is the requirement for the liquid flow rate information to be supplied from an external source. There are ways of finding individual water and HCL flow rates from an external source, e.g. test separator historical data or tracer dilution methods. However, these are spot checks with significant uncertainties. Their use with an orifice meter wet gas correction makes the (often unrealistic) assumption that they are valid values at the time of use, i.e. that the liquid flow rate has not changed since the time of measurement. An error in liquid flow rate prediction has an adverse effect on the wet gas correlation gas flow rate prediction.

Shell (de Leeuw [7]) suggested a Lockhart Martinelli parameter monitoring technique. By monitoring the ratio of the permanent pressure loss (PPL) to traditional DP (a ratio called the Pressure Loss Ratio, or “PLR”) it is potentially possible to observe a shift in the Lockhart Martinelli parameter. By definition, the PLR must be within the range: $0 \leq \text{PLR} \leq 1$. ISO 5167 shows that an orifice meters PLR in single phase flow is dictated by the beta ratio (β) and discharge coefficient (see equation 18).

$$\text{PLR} = \frac{\sqrt{1 - \{\beta^4(1 - C_d^2)\}} - C_d\beta^2}{\sqrt{1 - \{\beta^4(1 - C_d^2)\}} + C_d\beta^2} \quad \text{--- (18)}$$

Whereas for a given meter the beta ratio is set, the discharge coefficient can change with Reynolds number. However, the discharge coefficient and therefore the PLR have a relatively low sensitivity to the Reynolds number. Hence, an orifice meters single phase PLR value can be practically assumed constant for all single phase flow conditions. Shell / de Leeuw showed that Venturi meters also had a constant single phase flow PLR value but that it increased with an increasing Lockhart Martinelli parameter. Therefore, the PLR could be used (with Venturi meters at least) to monitor for changes in Lockhart Martinelli parameter.

During the CEESI wet gas flow JIP (1999-2002) four 4” orifice meter beta ratio plates were tested (see Table 6 in the Appendix). In order to investigate the applicability of the Lockhart Martinelli parameter monitoring system to orifice meters Shell requested the PLR be read for each orifice meter. Figure 9 shows the test set up. The downstream tap (off screen at 6D behind the plate) was used to measure the permanent pressure loss. The results were mixed. Venturi and orifice meters are both generic DP meters operating on the same physical principle. However, the Venturi meter has a low permanent pressure loss (i.e. a low PLR) and an orifice meter has a relatively high permanent pressure loss (i.e. a relatively high PLR). Unlike Venturi meters which all have low PLR’s (in the 0.05 to 0.2 range) orifice meter PLR’s are heavily dependent on the beta ratio. A lower beta ratio has a higher single phase PLR. Therefore, the four beta ratio orifice meters chosen had different single phase PLR values. Figure 30 to 33 show the CEESI JIP results. The ISO single phase PLR prediction is included.

For dry gas flow the ISO predictions are clearly close to the actual results. The 0.34 & 0.4 beta ratio orifice meters had very high PLR values > 0.8 . It was found that for these meters the Lockhart Martinelli parameter had no discernable effect on the PLR. This is suspected to be due to the single phase baseline being so close to the theoretical maximum of unity. As the Lockhart Martinelli parameter increases there is a small difference between the PLR baseline and the maximum physically possible PLR (i.e. unity). Therefore for small beta ratio orifice meters, monitoring the PLR does not give any useful information about the Lockhart Martinelli parameter value. However, for the larger two beta ratios of 0.5 & 0.68 the difference between the dry gas PLR value and unity was great enough that some relationship between the PLR and Lockhart Martinelli parameter was observed. The relationship was highly dependent on the gas to liquid density ratio. The higher the gas to liquid density ratio the closer the wet gas PLR to the dry gas PLR. The lower the gas to liquid density ratio the more sensitive the PLR vs. Lockhart Martinelli parameter relationship became. A slight gas densiometric Froude number effect was also evident (not

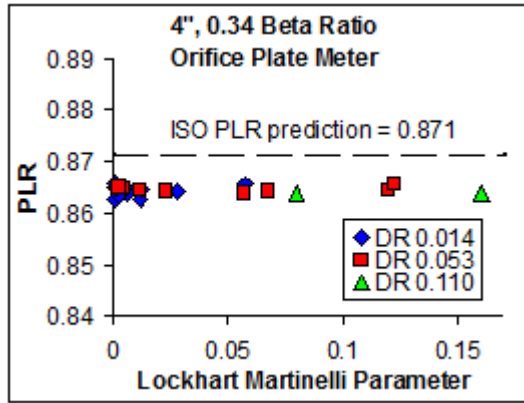


Fig 30. PLR vs. X_{lm}, 4", 0.34 beta ratio.

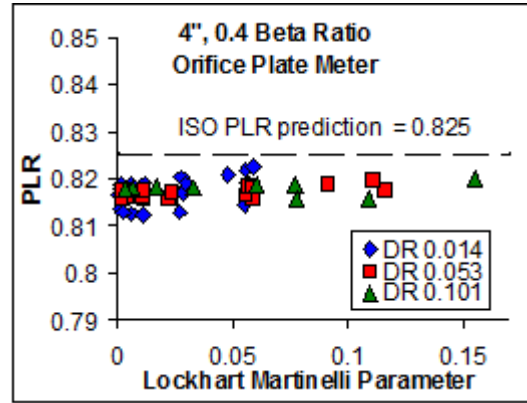


Fig 31. PLR vs. X_{lm}, 4", 0.40 beta ratio.

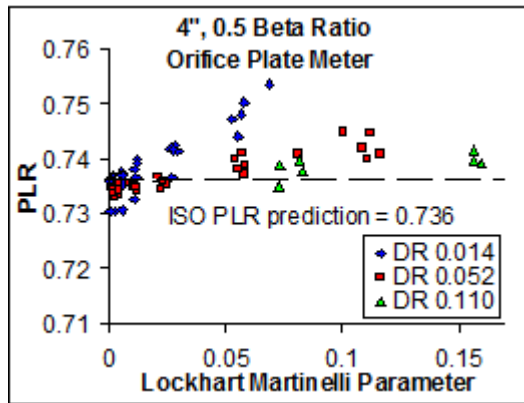


Fig 32. PLR vs. X_{lm}, 4", 0.50 beta ratio.

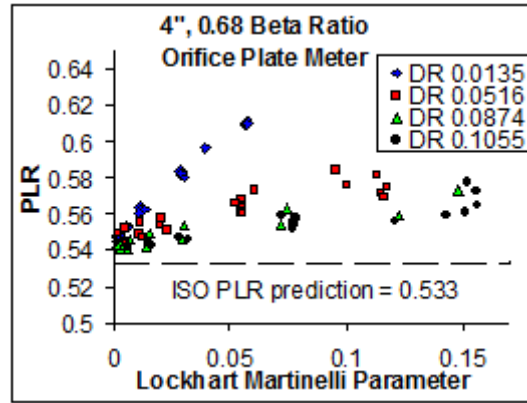


Fig 33. PLR vs. X_{lm}, 4", 0.68 beta ratio.

shown). For a set Lockhart Martinelli parameter and density ratio higher gas densiometric Froude numbers tended to have PLR values closer to the single phase PLR values. It is postulated that as the gas to liquid density ratio and gas densiometric Froude number increase the flow pattern tends to homogenous flow, which is a pseudo-single phase flow, and hence the PLR tends to the single phase PLR value. Therefore, when using orifice meters with wet gas flow there is some limited benefit in reading the PLR to monitor the Lockhart Martinelli parameter. The technique is more effective for larger beta ratios and lower gas to liquid density ratio and gas densiometric Froude numbers.

7. Liquid Flow Rate Biases and the Effect on DP Meter Wet Gas Correlation

There can be considerable uncertainty associated with the liquid flow rate prediction. Any bias in the liquid flow rate prediction creates a follow on bias on the gas flow rate correction uncertainty. However, it can be shown (Steven [16]) that the lower a DP meters over-reading to Lockhart Martinelli parameter ("Murdock") gradient the lower that meters wet gas correlations sensitivity to the liquid flow rate uncertainty. Therefore, when comparing the de Leeuw (Venturi), Steven (cone) and this paper's orifice meter wet gas correlations the orifice meter is the least sensitive meter to the liquid flow prediction uncertainty. This is shown by a worked example:

Consider a 4" meter with a wet gas flow condition of a gas flow rate of 6 kg/s and a HCL flow rate of 3 kg/s. Say the gas density is 73.4 kg/m³ and HCL density is 806.8 kg/m³. Therefore, the Lockhart-Martinelli parameter is 0.1508, the gas to liquid density ratio is 0.091 and the gas densiometric Froude number is 3.57. Unlike orifice

meters, Venturi & cone meters have a wet gas flow performance dependent on the beta ratio. Therefore in order to correctly apply the de Leeuw, Venturi and Steven cone correlations assume a 4", 0.4 beta ratio Venturi meter and 4", 0.75 beta ratio cone meter. Let us consider using a 0.6 beta ratio orifice meter. This wet gas condition is selected to be a reasonable flow condition for all three DP meter designs and their associated wet gas flow meter correlations, thereby allowing a fair comparison.

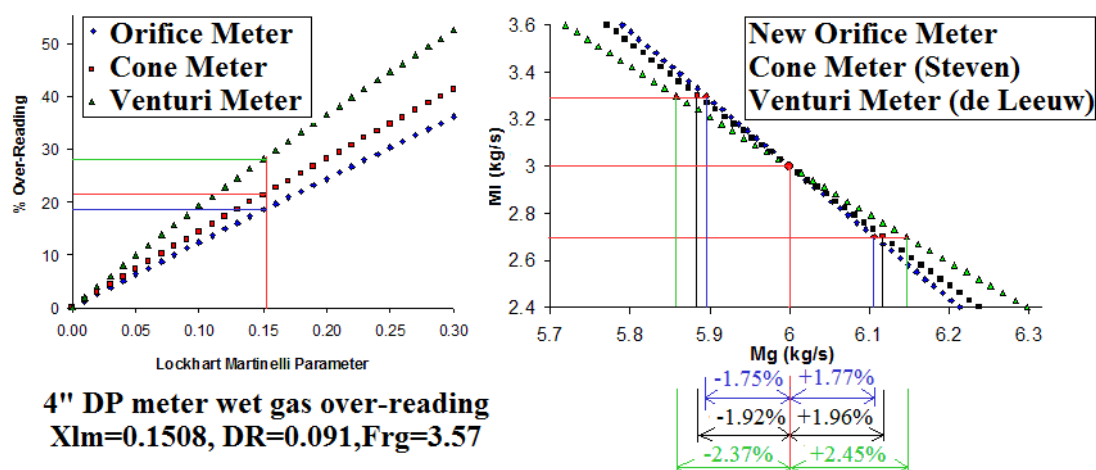


Fig 34. Sample comparison of an orifice, cone & Venturi meter.

All three correlations are said to have a gas flow rate prediction uncertainty of $\pm 2\%$. Therefore, as the stated uncertainties are the same, let us assume that all three correlations would give the same correct gas mass flow rate when the correct (i.e. no error) liquid mass flow rate information was applied. Figure 34 shows a comparison of the performance of the three meter types and correlations when the liquid mass flow rate estimate is ten percent high and low. It is known that the over-reading to Lockhart Martinelli parameter (Murdock) gradient, and hence the sensitivity to the Lockhart Martinelli parameter, is lowest for orifice meters, intermediate for cone meter and highest for Venturi meters. The affect on the gas flow rate prediction of having a $\pm 10\%$ error in the liquid flow rate prediction is dependent on the meters sensitivity to the Lockhart Martinelli parameter. Naturally, all three correlation liquid to gas mass flow slopes intersect at the correct result. However, the plots clearly show the difference in sensitivity of the meter correlations to varying liquid flow rate predictions. In this example the $\pm 10\%$ liquid flow rate error is seen to have a knock on error on the gas flow rate prediction of:

- $-1.75\%/+1.77\%$ for the orifice plate meter,
- $-1.92\%/+1.96\%$ for the cone type DP meter
- $-2.37\%/+2.45\%$ for the Venturi meter.

These uncertainties are in addition to the uncertainty rating of each correlation. Therefore, the orifice meter is seen to be the most insensitive DP meter to the liquid flow rate prediction uncertainties.

8. CEESI 8", 0.6 beta ratio multiphase wet gas orifice meter tests

In 2011 CEESI commissioned a nominally 8" multiphase wet gas flow test facility. An 8", 0.69 beta ratio orifice meter was installed as a commissioning meter. Figure 35 shows the installation. Table 13 in the Appendix shows the scope of this initial multiphase wet gas flow commissioning run.



Fig 35. CEESI 8" orifice meter test

The orifice meter correlation shown on page 20 is derived from 2" through 4" orifice meter data. The effect of diameter (i.e. meter size) on any DP meter type wet gas flow response is as yet not understood. It was not therefore guaranteed that the above correlation would be appropriate for a 8", 0.69 beta ratio orifice meter.

Nevertheless, for interest the 8" data was applied to the correlation. The results are shown in Figure 36. It can be seen that this *preliminary* look at 8", 0.69 beta ratio orifice meter wet gas performance suggests that the above correlation (page 20) is predicting the 8" orifice meters wet gas over-reading correctly.

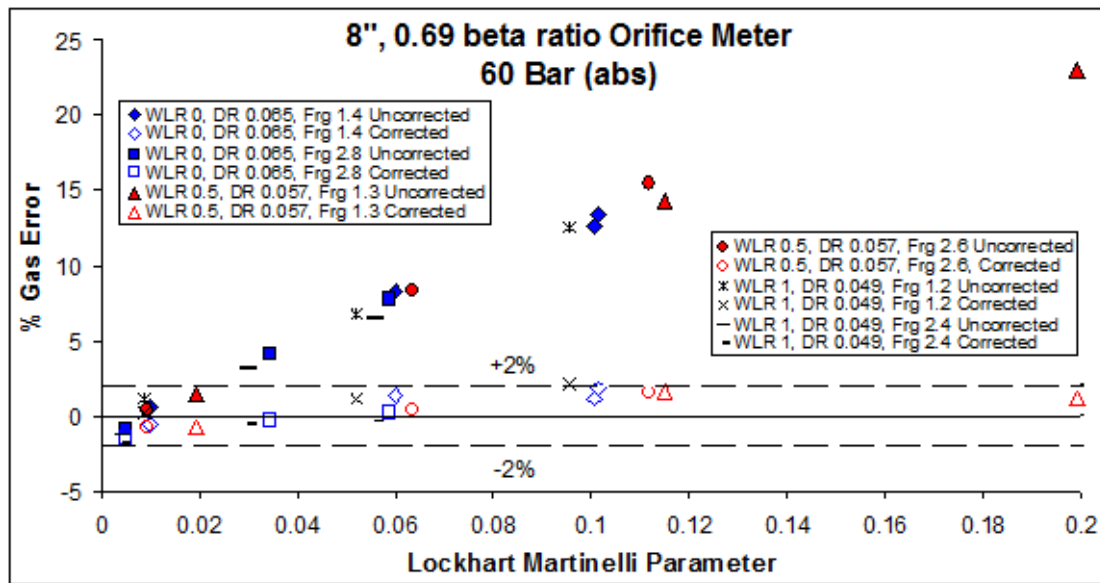


Fig 36. Preliminary CEESI multiphase wet gas flow data from an 8" orifice meter.

However, although 18 of the 19 points are corrected to $\pm 2\%$ (i.e. at $94.7\% \approx 95\%$ confidence) it should be recognised that this is a very small initial 8" orifice meter data set. Some of the data were at $X_{LM} \leq 0.02$ which is often ignored in orifice meter wet gas flow research. The typical under-reading as described by Ting [15] for $X_{LM} \leq 0.01$ is evident. In this particular data set the gas with water only and gas with HCL only data were only recorded up to a approximately half of the facility flow range at $X_{LM} \leq 0.12$. Therefore, the common trends of the gas densimetric Froude number and liquid properties affecting the over-reading are masked by the low Lockhart Martinelli parameter data. In this available data set only a single 50% WLR_m data point reached $X_{LM} = 0.2$. Hence, although these preliminary data show that the 8" meter has the same general response as 2" through 4" meters it should be understood that this is a small preliminary test and no final conclusions should be drawn from it.

It is noticeable that with the exception of the $X_{LM} \leq 0.02$ data the correlation tends to correct to 0 to +2% within the $\pm 2\%$ range. As yet it is not known if this is just randomness in the scatter or if this will turn out to be an early indication of the over-reading systematically increasing slightly as the meter size increases. At the time of writing the authors do not know. However, as the orifice meter is installed as a check meter in the CEESI 8" multiphase wet gas flow facility it is hoped that the answer to this will be found in the near future. For the moment the definite finding from this 8" orifice meter test is the important result that the 8" orifice meter continued to operate in a very similar way to the smaller meters and it did not have a drastic change in performance due to the increase in size.

8. Conclusions

The wet gas flow performance of orifice meters is of importance to the oil and gas production industry. However, there is an impression that the wet gas flow performance of orifice meters has been to some extent ignored owing to more emphasis being placed on the performance of Venturi and cone meters. Nevertheless, there is now substantial evidence that the performance of the orifice meter is relatively good in wet gas flows. As long as the orifice plate does not sustain damage, the orifice meters wet gas flow performance is repeatable, reproducible and therefore predictable. Concerns regarding an orifice meters DP signal stability and the potential damming effect in wet gas have been shown to be largely unfounded.

It has been found that like all DP meters the orifice meter is affected by the Lockhart Martinelli parameter, the gas to liquid density ratio, the gas densimetric Froude number and the water liquid ratio. The orifice meter is also affected by the beta ratio, although unlike other DP meters this effect is so small that it can be practically ignored. This has significant practical advantage over other DP meter designs. The other DP meter wet gas correlations are for dedicated beta ratios. That is if they are used with other beta ratios they can induce a significant bias on the gas flow prediction. This is not so with the orifice meter.

The 2" through 4" orifice meter correlation given in this paper has been shown to cover a wide beta ratio range, i.e. $0.25 \leq \beta \leq 0.73$. It has also been shown in this paper that the water liquid ratio effect on an orifice meter wet gas over-reading is almost linear and hence an orifice meter wet gas correlation can account for it. Currently, no research has shown this to be so for any other DP meter design. Furthermore, the publicly available wet gas flow data set for orifice meters is far more comprehensive than for any other DP meter design. The massed data sets from different institutions, test facilities and owned by many different organisations have shown a remarkable reproducibility. The use of the pressure loss ratio (or "PLR") to monitor the Lockhart Martinelli parameter through an orifice meter has been shown to be potentially useful for $\beta \geq 0.5$, but not useful for $\beta < 0.5$.

Orifice meters have been shown to offer an advantage over using other DP meter designs in wet gas flow. The orifice meter is less sensitive to changes in Lockhart Martinelli parameter and therefore the orifice meter wet gas correlations are less sensitive to errors in the liquid flow rate predictions. Finally, preliminary data from CEESI's 8" multiphase wet gas flow facility suggests that the 8" orifice meter operates with wet gas flow in the same generic way as the smaller orifice meters.

Acknowledgements

The authors acknowledge the contributions of BP, CEESI, Chevron, ConocoPhillips Emerson Process, Sick Maihak and the sponsors of the TÜV NEL and CEESI 1999 – 2002 wet gas JIP's in making data sets available for analysis.

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Appendix: Orifice plate meter wet gas flow data sets and their ranges.

Table 1 – Orifice meter, CEESI, 3", various beta (ConocoPhillips)

Parameter	Range
Pressure	6.7 to 78.9 bara
Gas to liquid density ratio	0.0066 to 0.089
Fr_g range	0.22 to 5.31
X_{LM}	< 0.080
Inside full bore diameter	0.0783 m (3.083 inch)
Beta	0.2433, 0.3649, 0.4865, 0.7298
Gas / Liquid phases	Natural gas / Decane

Table 2 – Orifice meter, CEESI, 4", 0.680 beta (Chevron)

Parameter	Range
Pressure	32 to 57 bara
Gas to liquid density ratio	0.044 to 0.081
Fr_g range	0.67 to 7.25
X_{LM}	< 0.250
Inside full bore diameter	0.10226 m (4.026 inch)
Beta	0.6800
Gas / Liquid phases	Natural gas/ Stoddart Solvent

Table 3– Orifice meter, CEESI, 4", 0.497 beta (Chevron, ConocoPhillips, CEESI)

Parameter	Range
Pressure	17.2 to 59 bara
Gas to liquid density ratio	0.018 to 0.083
Fr_g range	0.62 to 2.78
X_{LM}	< 0.264
Inside full bore diameter	0.10226 m (4.026 inch)
Beta	0.4970 (nominal 0.5)
Gas / Liquid phases	Natural gas/ Stoddart Solvent

Table 3a– Orifice meter, CEESI, 4", 0.338 beta (Chevron, ConocoPhillips, CEESI)

Parameter	Range
Pressure	17.2 to 58.5 bara
Gas to liquid density ratio	0.017 to 0.084
Fr_g range	0.6 to 1.35
X_{LM}	< 0.264
Inside full bore diameter	0.10226 m (4.026 inch)
Beta	0.338 (nominal 0.34)
Gas / Liquid phase	Natural gas/ Stoddart Solvent

Table 4 – Orifice meter, CEESI, 4”, 0.683 beta (BP, 2005)

Parameter	Range
Pressure	60 bara
Gas to liquid density ratio	0.0648 only
Fr_g range	1.5 to 6.0
X_{LM}	< 0.340
Inside full bore diameter	0.10226 m (4.026 inch)
Beta	0.6831
Gas / Liquid phase	Natural gas/ Stoddart Solvent

Table 5– Orifice meter, CEESI, 2”, 0.516 beta (BP, 2005)

Parameter	Range
Pressure	53 to 58 bara
Gas to liquid density ratio	0.039 to 0.055
Fr_g range	0.87 to 4.65
X_{LM}	< 0.550
Inside full bore diameter	0.04928m (1.940 inch)
Beta	0.5155
Gas / Liquid phase	Natural gas/ Stoddart Solvent/water

Table 6 – Orifice meter, CEESI, 4”, various beta (CEESI wet gas JIP, 1999-2002)

Parameter	Range
Pressure	14 to 76 bara
Gas to liquid density ratio	0.014 to 0.111
Fr_g range	0.36 to 3.78
X_{LM}	< 0.180
Inside full bore diameter	4.026 inch
Beta	0.3414, 0.4035, 0.4965 & 0.6826.
Gas / Liquid phase	Natural gas/ Decane

Table 7 – Orifice meter, NEL, 4 inch, beta 0.660 (NEL wet gas JIP, 2005)

Parameter	Range
Pressure	16.2 to 62.6 bara
Gas to liquid density ratio	0.023 to 0.091
Fr_g range	1.06 to 5.46
X_{LM}	< 0.300
Inside full bore diameter	0.10228 m (4.027 inch)
Beta	0.6598
Gas / Liquid phase	Nitrogen / Exxsol D80

Table 8 – Orifice meter, NEL, 4 inch, beta 0.650 (Emerson Process, 2005)

Parameter	Range
Pressure	16.1 to 62.1 bara
Gas to liquid density ratio	$0.023 < DR < 0.09$
Fr_g range	$0.5 < Fr_g < 2.7$
X_{LM}	$0 \leq X_{lm} < 0.35$
Inside full bore diameter	0.10228 m (4.028 inch)
Beta	0.650
Gas / Liquid phase	Nitrogen / Exxsol D80

Table 9 – Orifice meter, CEESI, 3 inch, beta 0.517 (Sick Maihak, 2010)

Parameter	Range
Pressure	13.3 to 56.7 bara
Gas to liquid density ratio	$0.013 < DR < 0.061$
Fr_g range	$0.8 < Fr_g < 4.02$
X_{LM}	$0 \leq X_{lm} < 0.21$
Inside full bore diameter	0.07366 m (2.9 inch)
Beta	0.5172
Gas / Liquid phase	Nitrogen / Exxsol D80

Table 10 – Orifice meter, CEESI, 4 inch, beta 0.620 (BP/CoP/CEESI, 2010)

Parameter	Range
Pressure	65 to 71 bara
Gas to liquid density ratio	$0.054 < DR < 0.082$
Fr_g range	$1.9 < Fr_g < 5.3$
X_{LM}	$0 \leq X_{lm} < 0.25$
Inside full bore diameter	0.10228 m (4.028 inch)
Beta	0.620
Gas / Liquid phase	Nitrogen / Exxsol D80 / Water

Table 11 – Orifice meter, CEESI, 4 inch, beta 0.620 (CEESI commissioning, 2007)

Parameter	Range
Pressure	13.8 to 75.2 bara
Gas to liquid density ratio	$0.010 < DR < 0.083$
Fr_g range	$0.7 < Fr_g < 4.7$
X_{LM}	$0 \leq X_{lm} < 0.27$
Inside full bore diameter	0.10228 m (4.028 inch)
Beta	0.620
Gas / Liquid phase	Nitrogen / Exxsol D80 / Water

Table 12 – Orifice meter, CEESI, 4 inch, beta 0.620 (3rd party test, 2010)

Parameter	Range
Pressure	14.4 to 75.6 bara
Gas to liquid density ratio	$0.011 < DR < 0.082$
Fr_g range	$0.7 < Fr_g < 5.1$
X_{LM}	$0 \leq X_{lm} < 0.29$
Inside full bore diameter	0.10228 m (4.028 inch)
Beta	0.620
Gas / Liquid phase	Nitrogen / Exxsol D80 / Water

Table 13 – Orifice meter, CEESI, 8 inch, beta 0.6 (CEESI commissioning 2011)

Parameter	Range
Pressure	61 bara
Gas to liquid density ratio	$0.049 < DR < 0.065$
Fr_g range	$1.4 < Fr_g < 2.8$
X_{LM}	$0 \leq X_{lm} < 0.2$
Inside full bore diameter	0.2027 m (7.981 inch)
Beta	0.69
Gas / Liquid phase	Nitrogen / Exxsol D80 / Water