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Liquid Property and Diameter Effects on DP Meter Wet Gas Over-Readings

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1 INTRODUCTION

Wet gas flow metering technologies are important to the natural gas production industry. The state of the art of wet gas metering is steadily changing but it is generally true to say that the majority of the wet gas meter designs in some way utilize Differential Pressure (DP) meter technologies. Wet gas flows affect the gas flow predictions of all single phase gas flow meters but it has been found by experiment that DP meter designs are relatively reliable meters for wet gas flow applications. Whereas many gas meter designs fail to give any output or give erroneous unrepeatable gas flow rate predictions when used with wet gas flow the DP meter type continues to operate giving incorrect but repeatable gas flow rate predictions.

Over the last 50 years understanding of the phenomena affecting the performance of generic DP meters when exposed to wet gas flow has been developed. There are many papers on this subject and the effect on generic DP meters of varying several different wet gas flow parameters is now reasonably well understood. From this knowledge industry has developed different methods of metering wet gas flows utilizing DP meters. Many wet gas flow meter designs utilize one of four general concepts:

1) Use a stand alone DP meter and obtain the liquid flow rate information from an independent source (i.e. tracer dilution methods, test separator data etc.). Here, if the liquid induced gas flow rate prediction error for a given liquid flow rate at known flow conditions (i.e. pressure, temperature, etc.) has been previously found by experimental, the gas flow rate can be derived.

2) Use a stand alone DP meter with a downstream tapping. Under some wet gas flow conditions the ratio of the standard read DP to the meters permanent pressure loss has a relationship to the liquid content of the wet gas flow. Therefore, with suitable physical modeling and / or experimental data fitting the gas and liquid flow rates can be derived.

3) Use two dissimilar meters in series. Both meters (of which at least one is always a DP meter) will have their gas flow prediction adversely affected by the presence of liquid. As long as these two dissimilar meters react in a significantly different ways to the wet gas flow, and experimental data has previously shown each meters wet gas flow performance, the gas and liquid flow rates can be derived.

4) Use a DP meter with an imbedded phase fraction device (e.g. capacitance, conductance, gamma ray absorption systems etc.) in the meter body. From suitable physical modeling and experimental data fitting the DP meter / phase fraction device output is said to be capable of predicting the gas and liquid flow rates (and in some cases a ratio of water to hydrocarbon liquid flows).

Note that all of these wet gas flow metering approaches utilise DP meter technology. All four approaches can benefit from a more comprehensive understanding of the performance of DP meters when exposed to wet gas flows. Different manufacturers produce different meter designs based on one of these general metering principles and they may choose to use unique methodologies in processing the information. However, fundamentally the concepts are similar.

The range of industrial wet gas flow metering conditions is extremely large. There are requirements for wet gas meters of all sizes which can be orientated in any way and these meters can experience any ranges of pressure, temperature, fluid properties and liquid and gas flow rates. The existing wet gas test facilities can only cover small ranges of this vast field of flow conditions. The meter manufacturers and users are therefore often forced to carry out large extrapolations on the existing data sets at the expense of uncertainty claims.

The significant amount of research that has been carried out into the response of different DP meter designs to wet gas flow strongly suggests that all DP meters (excluding laminar flow elements) have the same generic response to wet gas flow. That is, the various DP meters have liquid induced gas flow rate prediction errors that all tend to increase or decrease in the same direction as particular wet gas flow parameters are varied. The precise scale of this error for a constant wet gas flow condition is different between different DP meter designs but the trends of how the meters react to varying flow parameters seem to be the same. How the generic DP meter used for wet gas flow metering responds to changes in the liquid loading, pressure and gas velocity is fairly well understood. The influence of the size of the primary element relative to the pipe size (i.e. the "beta ratio") is also fairly well understood. Less well understood is the reaction of the generic DP meter to changes in a wet gas flows liquid properties, meter size (i.e. inlet diameter or "scaling effects") and meter orientation. There has been a limited amount of research into the affect on wet gas flow DP meters when the liquid is changed from light hydrocarbons to water (i.e. gas with hydrocarbon liquid only and gas with water only). The literature has very little information on the industrial relevant case of gas with hydrocarbon liquid ***and*** water. Likewise there is a dearth of publicly available information on the effect of meter size or orientation on the generic DP meters wet gas flow response.

As the Venturi meter is a commonly used DP meter with wet gas flow this paper introduces the initial research carried out by CEESI on the response of the Venturi meter to gas with hydrocarbon liquid ***and*** water flow, to changing the Venturi meter size (i.e. inlet diameter) and to changing the meters orientation.

2 WET GAS DEFINITIONS

If the gas and liquid phase flows of a wet gas flow were imagined to flow alone then both phases would have single phase Reynolds numbers. Such dimensionless groups are:

$$\mathrm{Re}_{sg} = \frac{\rho_g U_{sg} D}{\mu_g} = \frac{\sup erficial\ gas\ inertia}{gas\ viscous\ force} \text{ --- (1)} \qquad \text{where } U_{sg} = \frac{\dot{m}_g}{\rho_g A} \text{ --- (2)}$$

$$\mathrm{Re}_{sl} = \frac{\rho_l U_{sl} D}{\mu_l} = \frac{\sup erficial\ liquid\ inertia}{liquid\ viscous\ force} \text{ ---(3)} \qquad \text{where } U_{s\ell} = \frac{\dot{m}_\ell}{\rho_\ell A} \text{ --- (4)}$$

where $\dot{m}_g$ and $\dot{m}_l$ are the gas and liquid mass flow rates respectively, ρ_g and ρ_l are the gas and liquid densities respectively, μ_g and μ_l are the gas and liquid viscosities respectively, U_{sg} and U_{sl} are the gas and liquid superficial velocities respectively, D is the inlet diameter and A is the inlet cross sectional area of the DP meter.

Gas application DP meters use a generic DP meter flow equation (5) which includes an expansibility factor (ε) and a discharge coefficient (C_d):

$$\dot{m}_g = EA_t\varepsilon C_d\sqrt{2\rho_g \Delta P_g} \quad \text{--- (5)}$$

where E is the velocity of approach (a geometric constant), A_t is the minimum cross sectional (or "throat") area and ΔP_g is the differential pressure (or DP) between the inlet and low pressure port in the vicinity of the throat. Single phase flow expansibility is in part a function of the DP and the discharge coefficient is a function of the single phase gas flow Reynolds number. The Reynolds number is a function of the flow rate (see equations 1 & 2). This means that the flow rate and associated Reynolds number are calculated by iteration. If a gas DP meter is operated with a wet gas flow with no correction factor used, the liquid presence affects the differential pressure read. This wet gas / two-phase flow differential pressure (ΔP_{tp}) is different to the differential pressure that would have been read if the gas flowed alone (ΔP_g). The application of this wet gas DP (ΔP_{tp}) value in the gas flow equation (5) results in a wet gas flow expansibility value ε_{tp}, and the iteration converging on an incorrect gas Reynolds number (Re_{tp}) and gas flow rate. This uncorrected gas mass flow rate prediction is often called the *apparent* gas mass flow, $\dot{m}_{g,apparent}$.

Wet gas flow is defined here as any gas and liquid flow that has a Lockhart-Martinelli parameter, X_{LM}, less than 0.3 [1]. The Lockhart-Martinelli parameter is defined as:

$$X_{LM} = \sqrt{\frac{Superficial\ \ Liquid\ \ Inertia}{Superficial\ \ Gas\ \ Inertia}} = \frac{\dot{m}_\ell}{\dot{m}_g}\sqrt{\frac{\rho_g}{\rho_\ell}} \quad \text{--- (6)}$$

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

$$DR = \rho_g / \rho_\ell \quad \text{--- (7)}$$

The gas densiometric Froude number (equation 8) and liquid densiometric Froude number (equation 9) are often used to represent a non-dimensional gas and liquid velocity parameters respectively. In these equations, *g* is the gravitational constant (9.81m/s^2).

$$Fr_g = \sqrt{\frac{Superficia\ l\ Gas\ Inertia}{Liquid\ Gravity\ Force}} = \frac{U_{sg}}{\sqrt{gD}}\sqrt{\frac{\rho_g}{\rho_l - \rho_g}} = \frac{\dot{m}_g}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_g(\rho_l - \rho_g)}} \quad \text{--- (8)}$$

$$Fr_l = \sqrt{\frac{Superficia\ l\ Liquid\ Inertia}{Liquid\ Gravity\ Force}} = \frac{U_{sl}}{\sqrt{gD}}\sqrt{\frac{\rho_l}{\rho_l - \rho_g}} = \frac{\dot{m}_l}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_l(\rho_l - \rho_g)}} \quad \text{--- (9)}$$

Note that the ratio of the liquid and gas densiometric Froude numbers gives the Lockhart Martinelli parameter (i.e. equation 6). The modified Weber number (equation 10) has been suggested [1] as a possible wet gas flow parameter to account for surface (or interfacial) tension effects. Note σ_l denotes the liquid interfacial tension. In reality surface tension values for set liquids with air at atmospheric conditions are reasonably well known but there is little in the literature regarding the interfacial tension between various hydrocarbon liquids and natural gas at elevated pressures and temperatures.

$$We_{tp} = \frac{Gas\ \ Inertia\ \ \ Forces}{Surface\ \ Tension\ \ \ Forces} = \frac{\dot{m}_g^{\,2}}{\sigma_l \rho_g D^3} \quad \text{--- (10)}$$

Note that the equations above all assume one liquid component. However, in wet natural gas flow production there is often hydrocarbon liquid and water present with the natural gas. In such a case the liquid mass flow is simply the sum of the hydrocarbon liquid ($\dot{m}_{hl}$) and the water ($\dot{m}_w$) flow rates. There is a question on what liquid density, viscosity and interfacial tension values to use? It is commonly ***assumed*** that at moderate to high gas flow rates typical of hydrocarbon production the liquids are well mixed and therefore the liquid can be considered a homogenous mix of water and hydrocarbon liquid. In this case averaged liquid properties are often assumed (with little experimental evidence that this assumption is valid).

A homogenous liquid density ($\rho_{l\,\mathrm{hom}\,ogenous}$) calculation is offered by ASME [1]. This takes the ratio of water to total liquid mass flow (equation 11) and substitutes it into the homogenous liquid density equation 12. Note ρ_{hl} and ρ_w denote the hydrocarbon liquid and water densities respectively.

$$x_l = \frac{\dot{m}_w}{\dot{m}_w + \dot{m}_{hl}} = \frac{\dot{m}_w}{\dot{m}_{l\,total}} \quad \text{--- (11)} \qquad \rho_{l\,\mathrm{hom}\,ogenous} = \frac{\rho_{hl} * \rho_w}{\rho_w (1 - x_l) + x_l \rho_{hl}} \quad \text{--- (12)}$$

However the validity of the assumption that the liquids are perfectly mixed will be questioned in this paper. The authors know of no published or generally agreed and accepted expressions for liquid viscosity or interfacial tension when the liquid phase of a wet gas flow is a water and liquid hydrocarbon combination.

Water cut is defined by ASME [1] as the "water volume to total liquid volume flow rate *at standard conditions*". However, the technologies that measure the quantity of water in the water / hydrocarbon liquid mixture of a wet gas flow tend to measure the water to total liquid volume flow rate at *flowing conditions*. This is generally called the WLR (i.e. water liquid ratio). There is a tendency for the phrases WLR and water cut to be used as equivalent terms. Caution should be used here as at elevated pressure and temperatures there can be a significant difference between the terms. The WLR needs to be converted to the water cut by use of PVT calculations. In this paper we will use the WLR to discuss the effect of water / hydrocarbon liquid mixtures on a Venturi meters wet gas flow response.

DP meters in wet gas flows tend to have a positive bias or *over-reading* on their gas flow rate prediction. That is, the uncorrected gas mass flow rate prediction (i.e. the apparent gas mass flow, $\dot{m}_{g,apparent}$) is usually greater than the actual gas mass flow rate of the wet gas flow. The "over-reading" is the ratio of the apparent to actual gas flow rate. Equations (13) and (14) show the over-reading (OR) and percentage over-reading.

$$OR = \frac{\dot{m}_{g,apparent}}{\dot{m}_g} \cong \sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} \quad \text{--- (13)} \qquad OR\,(\%) = \left(\frac{\dot{m}_{g,apparent}}{\dot{m}_g} - 1 \right) * 100\% \cong \left(\sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} - 1 \right) * 100\% \quad \text{--- (14)}$$

The concept of the DP meter wet gas flow "over-reading" is *one* method of quantifying the effect that the wet gas flow conditions will have on a single phase DP meter. It is necessary to quantify and predict the differential pressure that a DP meter will produce with a particular wet gas flow condition. This allows a correlation to be fitted to a physical model (or a blind data fit) thereby allowing the differential pressure produced to be related to the flow conditions including the gas and liquid flow rates.

In order to quantify the effect various individual wet gas parameters have on a DP meters output, a frame of reference (or "baseline") is required to allow the measurement of the relative differences between the differential pressures produced when varying different wet gas parameters. The frame of reference chosen is in fact rather arbitrary. The wet gas meter designs that utilize the first three generic design concepts listed in the introduction all tend to use the known single phase gas flow performance of the DP meter as the baseline. That is, for any wet gas flow condition, a thought experiment is conducted where the gas phase is imagined to flow alone through the meter. The known gas flow performance is the frame of reference when quantifying the actual wet gas flow meter performance. This is the "over-reading" and one method of quantifying the DP meters wet gas flow performance. However, this is not the only method available to analyze the wet gas performance of DP meters. Other frames of reference are available and equally valid.

The total combined "bulk" flow can also be used as the baseline. This total flow could alternatively be considered by thought experiment to be a flow of all gas, all liquid or a homogenous pseudo-single phase flow. The flow is imagined to flow through the meter in whatever state that has been chosen and the known single phase performance is the frame of reference when quantifying the actual wet gas flow meter performance.

The wet gas meter manufacturers that utilize the fourth generic design concept listed in the introduction tend to keep the details of the flow calculation procedures as proprietary information. However, several manufacturers talk of using the DP meters reading to predict a “bulk” flow rate estimate and most claim to not use the concept of a DP meter “over-reading”. Therefore, they use different frames of reference to the other wet gas meter designs. Nevertheless, as the frame of reference is arbitrary, a DP meters wet gas flow performance can be expressed using *any* frame of reference. That is, any DP meter data set can be expressed using *any* of the various valid baselines. Crucially, it should be understood that although the outcome of using different frames of reference and physical modeling or neural nets is different final calculation procedures, the physical phenomena effects of each wet gas flow parameter must still be fully accounted for in some way in *all* wet gas meter design calculation procedures. That is, if data analysis using *any* frame of reference identifies that a given wet gas flow parameter affects the differential pressure produced by the meter *then this is true independently of the frame of reference used* and all wet gas meter designs using that DP meter type must in some way account for it. It must therefore be understood that although the authors of this paper have chosen to use the over-reading concept to analyze the Venturi meters wet gas performance the affect on the meters output found for each wet gas parameter would have been found regardless of what arbitrary baseline was chosen. Hence the results shown here are equally valid for all wet gas DP meter designs regardless of the frame of reference used. Therefore, all DP meter based wet gas meter designs must account for the wet gas flow effects regardless of what analysis tool first discovered the effect.

3 HORIZONTAL AND VERTICAL UP FLOW PATTERNS

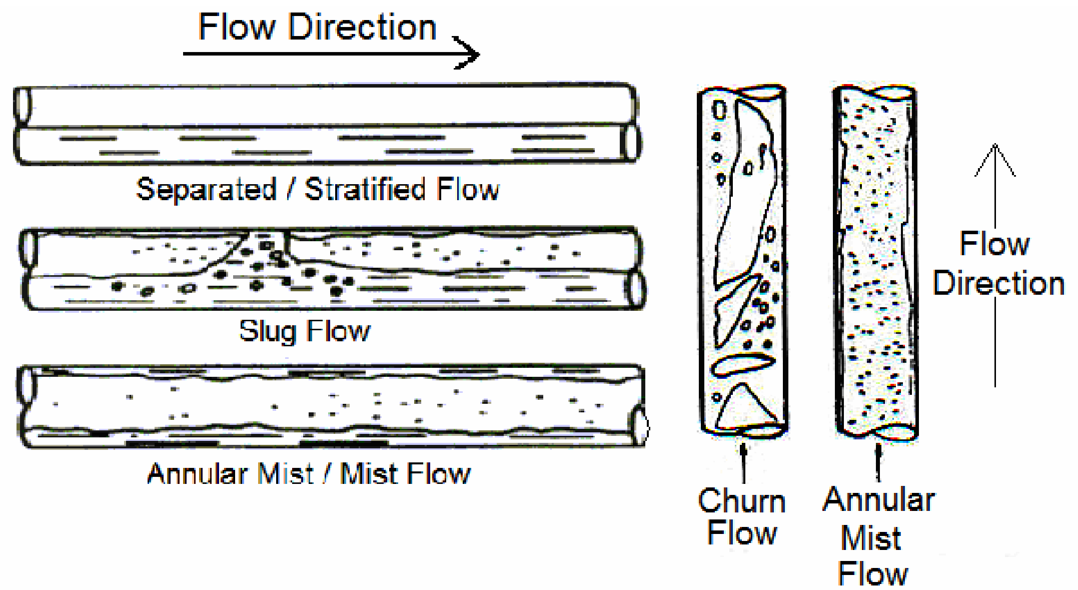

Fig 1. Typical Wet Gas Horizontal and Vertical Up Flow Patterns.

It is becoming almost universally accepted that flow patterns influence the response of wet gas flow DP flow meters. It is therefore necessary to review flow patterns and flow pattern prediction methods.

When gas and liquids flow together in a pipe the description of the physical dispersion of the liquid phase through the gas phase is termed the “flow pattern” (or the “flow regime”). The flow pattern is determined by many physical factors which include pipe orientation, pipe diameter, the ratio of liquid and gas mass flow rates, the gas flow rate, the pressure and the gas and liquid fluid properties. Figure 1 shows the common horizontal and vertical up wet gas flow patterns and (in the experience of the author) the most common names for these flow patterns.

Figure 1 shows the three main horizontal flow patterns found with industrial wet natural gas production flows. The “stratified” or “separated” flow pattern occurs when the gravitational force on the liquid is dominant and the gas dynamic forces on the liquid phase are relatively small. This occurs at relatively low pressure and low gas flow rates. At higher pressure and / or faster flow rates (where the gas dynamic forces are higher) the gas dynamic forces can disturb the surface of a stratified flow and produce waves. These can be relatively large and at higher liquid loadings (i.e. the upper end of wet gas flow) the waves can periodically block the cross section of the pipe. This is termed “slug”[1] flow. At high enough pressure and gas flow rates any given liquid to gas mass flow rate ratio will become an annular mist flow as the gas dynamic forces become dominant over the gravitational force. Here the liquid is forced to the wall with the gas flowing through the central core. There is still a gravitational effect with the annular ring being thicker at the base of the pipe. This gas core has considerable concentration of entrained liquid droplets (that are continually being reabsorbed by and reproduced from the annular liquid ring flow). As the pressure and gas flow rates continue to increase for any given liquid to gas mass flow rate ratio the annular ring thins as a greater percentage of the liquid mass flow becomes entrained in the gas core flow. At this same time the average droplet size is reducing as the gas dynamic pressure breaks up the larger droplets. Eventually the liquid will be all entrained and the droplet size is very small. This is sometimes called “mist” flow or “dispersed” flow but usually due to the lack of ability in real world situations to confirm there is no liquid ring this is still called “annular mist” flow. The wall is still wetted but no substantial liquid flow is in the form of the annular ring. Although the flow is now a dispersed droplet flow, gravity will still causes a higher liquid droplet concentration at the base of the pipe. As the pressure and gas flow rates increase further the droplet concentration becomes more symmetrical as the average droplet diameter reduces until the flow is effectively a mist flow. Here the liquid flow has been effectively “atomized” and the flow is effectively a homogenous flow where the phases are so well mixed the flow acts as a pseudo-single phase flow. It should be noted that whereas increasing both the pressure and gas flow rates drives the wet gas flow towards homogenous flow holding one of these parameters steady and increasing the other will eventually lead to homogenous flow. However, note that the homogenous flow pattern is rare in industrial meter applications as this flow pattern requires an extremely high gas dynamic pressure.

The two typical vertical up wet natural gas flow patterns are shown in Figure 1. If the gas dynamic force does not dominant over the liquids weight (i.e. the pressure and flow rates are relatively low) then the wet gas flow will be inherently unstable. That is, if the gravitational force on the liquid phase is not overcome by significantly larger gas dynamic forces there will be continued acceleration and deceleration of the liquid as the two opposing forces counter each other. A given unit mass of liquid has gas dynamic forces applied to it forcing it up the pipe. At the same time its weight is opposing this motion. As the liquid accelerates up the pipe the velocity of the liquid relative to the average gas velocity (which is itself fluctuating with the constantly varying flow pattern) reduces resulting in a reduced shear force on the annular film and reduced drag force on the liquid droplets. At some point the gas dynamic force can not suspend the liquid and it falls back. (That is, the liquid is now locally flowing in the opposite direction to the gas flow – a situation called counter current flow.) However, this immediately starts to increase the relative velocity between the phases and hence the gas dynamic forces. At some point the gas dynamic forces will again overcome the liquids weight and again force the liquid phase up the pipe. This unstable flow pattern is termed “churn” flow as the liquid phase is continually being mixed or “churned” up. Although the liquid phase has significant changes in velocity (possibly including a portion or all of the liquid having a temporary change of direction) it should be understood that the over all average flow rate of both phases over a longer period of time is up flow. Attempting to meter a churn flow can be relatively difficult as the inherent instability of the flow can lead to instrument signals continually fluctuating.

[1] “Slug” flow should not be confused with “slugging” or “severe slugging”. They are separate phenomena. Slug flow is due to instabilities at the liquid / gas interface. “Slugging” is caused by periodic blocking of the flow by liquid build up in low lying areas. The resulting highly unstable flow with high velocity liquid plugs is significantly different to the smaller relatively low velocity liquid waves of slug flow.

However, in many industrial wet gas flows the pressure and flow rates are such that the gas dynamic forces easily over come the gravitational force on the liquid phase. Here the wet gas flow is a steady annular mist flow. As the gas dynamic pressure increase the annular mist flow tends to mist flow and homogenous flow as it does with horizontal flows. However, note that in the vertical case with the gravitational force being applied directly down the pipe there is a symmetry to the annular ring and droplet dispersion that doesn't exist with the horizontal annular mist flow pattern. It is for this reason that some designers locate phase fraction devices in vertical flow locations and some wet gas flow meters are installed in vertical up flows where symmetrical annular mist flow is expected.

No flow pattern sketches are shown for vertical down flow. With the gravitational force and gas dynamic forces complementing each other the wet gas vertical down flow can generally be considered to be mist flow. Nominally horizontal two phase flows with slight positive inclination angles promote slug formation and slight negative inclinations promote stratification. A positive or negative inclination from the horizontal of as little as one degree is reported [3] to cause noticeable effects on the flow pattern.

4 HORIZONTAL FLOW PATTERN MAPS

With flow patterns affecting the readings made by DP meters it can be of interest to predict the flow pattern that exists in any given flow condition. This is difficult and industry tends to use flow pattern maps as theoretical prediction of the flow patterns is prohibitively complex. Flow pattern maps are experimental observations plotted to various flow parameters. There is no literature discussing an attempt to theoretically predict the flow pattern of any given flow condition. It is known that many different parameters can affect the flow pattern. Taitel & Dukler [4] is a rare case where the flow pattern prediction for horizontal two-phase (i.e. gas and liquid) flow is only semi-empirical. For completeness, and because Taitel & Dukler's work will be used later when discussing diameter effects of DP meter wet gas meter performance, the Mandhane flow pattern map and the semi-empirical method of Taitel & Dukler are now discussed.

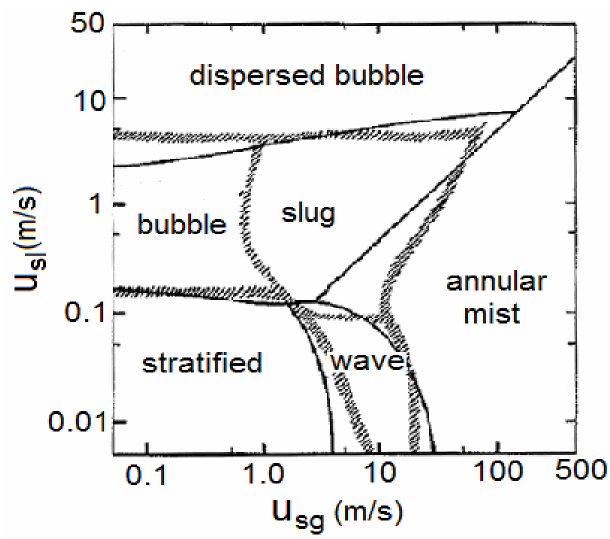

Fig 2. Taitel and Dukler Published Comparison of the Mandhane Map (thick lines) and Taitel & Dukler Horizontal Flow Theory for Air and Water in a 2.5 cm Pipe at Atmospheric Conditions (thin lines).

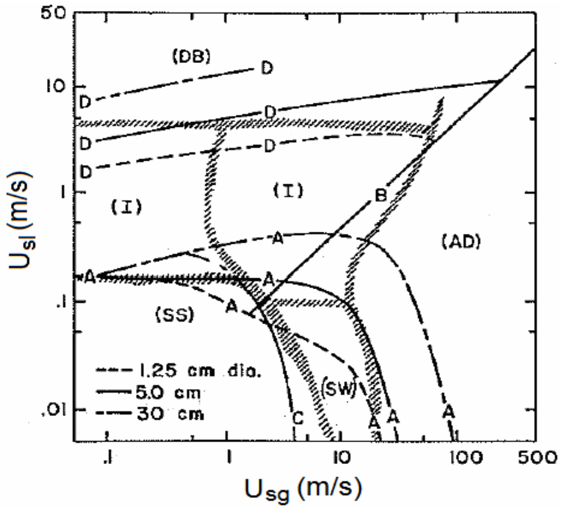

Figure 3a. Taitel and Dukler Published Graph Showing the Taitel and Dukler Horizontal Flow Theory Prediction for Different Pipe Diameters for Air and Water in a 2.5 cm Pipe at Atmospheric Conditions.

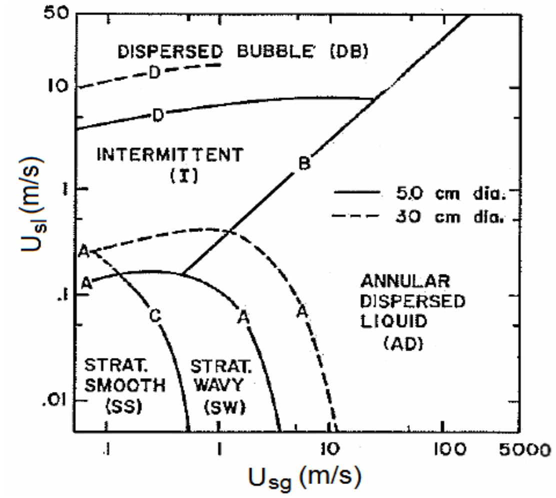

Figure 3b. Taitel and Dukler Published Graph Showing the Taitel and Dukler Horizontal Flow Theory Prediction for Natural Gas and Crude Oil at 30^o C and 68 Atmospheres.

The Mandhane flow pattern map is well known horizontal two phase flow pattern map used by engineers in the natural gas production industry. It is shown here (along with a Taitel and Dukler flow pattern prediction result) in Figure 2. The Mandhane map was created from observations of air and water at low pressures (close to atmospheric conditions). Here the axes are the superficial gas and liquid velocities (i.e. equations 2 and 4). Note that the Mandhane map is a general two-phase flow map. The flow patterns of elongated bubble and dispersed flow, meaning liquid with dispersed bubbles, are not flow patterns found with wet gas flows.

Taitel and Dukler [4] produced a calculation method for flow pattern prediction although the results can be plotted as a flow pattern map. As proof of the performance they compared their predictions for an air and water flow at atmospheric conditions through a 2.5 cm pipe diameter pipe to the predictions of the Mandhane flow pattern map. This is reproduced in Figure 2. Taitel & Dukler went on to use their prediction method to discuss the effects of pipe diameter and fluid properties on the flow pattern. They predicted that both parameters could significantly affect the flow pattern.

Taitel and Dukler [4] showed the predicted effect of changing pipe diameters for the set condition of air and water flow at atmospheric conditions (see Figure 3a). They also showed the situation when there were significantly different fluid properties and pipe diameters (see Figure 3b). The prediction for the wet gas flow region was that the larger the pipe diameter the more the tendency of a wet gas flow to remain stratified. The boundaries for the 5 and 30 cm pipes between air water at atmospheric conditions and natural gas and crude oil at 30^o C and 68 Atmospheres are significantly different suggesting that the pressure and the liquid properties may also affect the flow pattern.

If a wet gas flow meter is sensitive to changes in flow pattern then if proven correct, these Taitel and Dukler predictions will have direct consequences to the application of that wet gas flow meter design. That is, wet gas meter data fits based on experimental data from one meter size and fluid combination may need to be refitted to suitable experimental data for applications with other pipe sizes and fluid properties.

4 DIMENSIONAL ANALYSIS OF A WET GAS FLOW THROUGH A VENTURI METER

DP meter wet gas flow research has developed over 50 years with many of the researchers having little or no communication with each other. The various research projects tended to be isolated and each specific to a particular industrial problem. The general preferred procedure was modeling of a flow through a particular DP meter at set wet gas flow conditions followed by fitting experimental data to the model. This is a sound approach although the modeling inherently requires a set of assumptions to be made, e.g. perhaps the flow pattern is set at stratified flow, perhaps there is only one liquid component, perhaps the flow is horizontal only etc. etc.. The resulting wet gas flow DP meter systems are limited to these assumptions and the range of the data sets used to verify and data fit the flow models.

Wet gas flow through DP meters is, like most fluid mechanics problems, dependent on complex relationships between the physical shape of the system and the fluid flow parameters. One major question a researcher must ask is what factors influence the response of the DP meter? Then the question is what dimensionless groups are best suited for expressing these factors? One powerful analytical tool available to wet gas flow meter designers is dimensional analysis. However, no dimensional analysis was ever published by early researchers. Due to the compartmentalized history of DP meter wet gas flow development the existing dimensionless numbers were chosen by consequence of flow modeling alone (which is perfectly valid). The procedure of conducting a dimensional analysis of wet gas flow through a DP meter is out with the scope of this paper. However, the procedure was published by Steven [2] for a horizontally installed Venturi meter. The procedure and results can be summarized here in order to aid further discussion.

Sketches of a generic Venturi meters installed horizontally and vertically are drawn in Figure 4. The parameters considered as potentially influential on the DP meters response to wet gas flow are listed. If an influential parameter is missed then the dimensional analysis will still produce a result but it will not tell the full story. Therefore, all parameters that can be thought of as possibly being influential are added. If a parameter is added that does not in fact influence the DP meters response to wet gas flow then experimentation will show the resulting dimensionless group to be insensitive to that parameter, it can be dropped and no harm is done to the rest of the analysis. In this first analysis only one liquid component is considered. The case of two liquid components will be dealt with later.

It should be noted here that the Venturi meter analysis carried out by Steven did not include the orientation of the meter. This was not an oversight but due to the fact that the angle of which gravitational force is applied to the system is dimensionless (as radians have no units). Hence dimensional analysis can say nothing regarding the effect of orientation. Therefore, the dimensional analysis is independent of the meter orientation and the dimensional analysis conducted by Steven is valid for any orientation. The effect of orientation would be noticed at the stage of fitting experimental data. That is, any flow model data fit will only be applicable to the same orientation as the flow meter that supplied the experiment data unless it can be shown that orientation has no effect.

The dimensionless analysis gave the following relationship:

$$\Delta P_{tp} = \frac{\dot{m}_g^{\,2}}{2\rho_g A^2} f_1\left(\frac{\dot{m}_l}{\dot{m}_g}, \frac{\Delta\rho}{\rho_g}, \frac{\mu_g D}{\dot{m}_g}, \frac{\mu_l D}{\dot{m}_g}, \frac{\sigma_l \rho_g D^3}{\dot{m}_g^{\,2}}, \frac{d}{D}, \frac{L_c}{D}, \frac{L_t}{D}, \frac{L_d}{D}, \frac{e}{D}, \frac{\rho_g^2 D^5 g}{\dot{m}_g^{\,2}}, \frac{P}{\rho_g U_{sg}^2} \right) \text{ --}$$

(15)

where f_1 is some function that includes the terms inside the brackets. The form of this function must be determined experimentally. Re-arranging allows the following set of dimensionless groups found by various researchers (as expressed in section 2) to be derived from the original set of groups above:

$$\Delta P_{tp} = \frac{\dot{m}_g^{\,2}}{2\rho_g A^2} f_2\left(X_{LM}, \frac{\rho_g}{\rho_l}, Fr_g, \mathrm{Re}_{sg}, \mathrm{Re}_{sl}, We_{tp}, \beta, \frac{L_c}{L_t}, \frac{L_t}{L_d}, \frac{L_d}{D}, \frac{e}{D}, \frac{\Delta P_{tp}}{P} \right) \text{ --(15a)}$$

where f_2 is some function that includes the terms inside the brackets. The form of this function must be determined experimentally. Or, alternatively:

$$\dot{m}_g = \frac{A\sqrt{2\rho_g \Delta P_{tp}} * f_3\left(\mathrm{Re}_{tp}, \beta, \frac{L_c}{L_t}, \frac{L_t}{L_d}, \frac{L_d}{D}, \frac{e}{D}, \varepsilon_{tp} \right)}{f_4\left(X_{LM}, \frac{\rho_g}{\rho_l}, Fr_{g,} \mathrm{Re}_{sg}, \mathrm{Re}_{sl}, We_{tp}, \beta, \frac{L_c}{L_t}, \frac{L_t}{L_d}, \frac{L_d}{D}, \frac{e}{D} \right)} \text{ -- (15b)}$$

where f_3 & f_4 are functions that includes the terms inside the brackets. Note that $\beta = d/D$ is termed the "beta ratio" and e/D is commonly called the "relative roughness". Also note that the numerator of this equation 15b is, for a set geometry, the apparent gas mass flow rate, $\dot{m}_{g,apparent}$. Therefore equation 15b can be expressed as equation 15c. The form of the function f_4 must be determined experimentally.

$$\dot{m}_g = \frac{\dot{m}_{g,Apparent}}{f_4\left(X_{LM}, \frac{\rho_g}{\rho_l}, Fr_{g,} \mathrm{Re}_{sg}, \mathrm{Re}_{sl}, We_{tp}, \beta, \frac{L_c}{L_t}, \frac{L_t}{L_d}, \frac{L_d}{D}, \frac{e}{D} \right)} \text{ -- (15c)}$$

Here, the dimensionless groups found by various researchers conducting flow modeling are derived and others not yet accounted for by any published research are also suggested. Note that equation 15c is arranged to be in the general form of a DP meter wet gas over-reading correlation. The numerator is a representation of the generic DP meter gas equation used with wet gas flow and the denominator is in the form of the correction factor. Note that the correction factor (denominator) dimensionless groups can be split into two distinct sets, i.e. terms related to flow conditions and flow related to geometric terms:

$$f_4\left(\underbrace{X_{LM}, \frac{\rho_g}{\rho_l}, Fr_g, \mathrm{Re}_{sg}, \mathrm{Re}_{sl}, We_{tp}}_{\text{Flow Condition Terms}} \underbrace{\beta, \frac{L_c}{L_t}, \frac{L_t}{L_d}, \frac{L_d}{D}, \frac{e}{D}}_{\text{Geometric Terms}} \right)$$

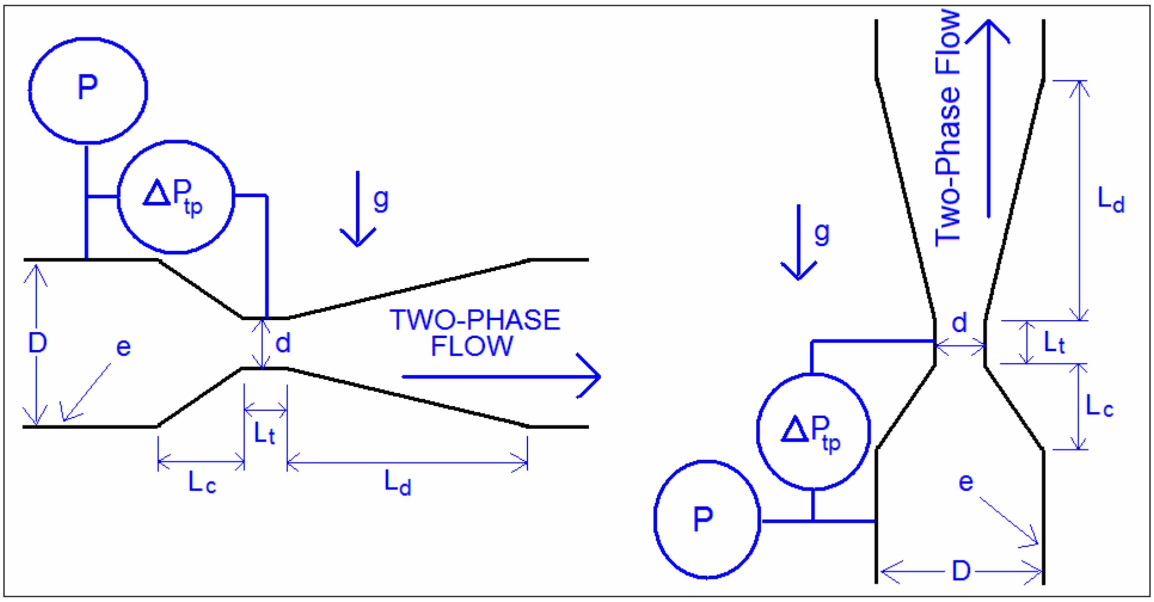

Figure 4. Sketches of Generic Venturi Meters with Horizontal and Vertical Up Flow.

The first list of dimensional groups analysed was for single liquid component wet gas flows:

ΔP_{tp} (i.e. the differential pressure from upstream to throat)	$\left(m/lt^2\right)$
$\dot{m}_g$ & $\dot{m}_l$ (i.e. the gas and liquid mass flow rates respectively)	$\left(m/t\right)$
ρ_g (i.e. the gas density)	$\left(m/l^3\right)$
$\Delta\rho$ (i.e. $\rho_l - \rho_g$ the difference between phase densities)	$\left(m/l^3\right)$
μ_g & μ_l (i.e. the gas and liquid viscosities respectively)	$\left(m/lt\right)$
σ_l (i.e. the liquid interfacial tension)	$\left(m/t^2\right)$
d (i.e. the Venturi inside bore throat diameter)	$\left(l\right)$
D (i.e. the Venturi inlet inside bore diameter)	$\left(l\right)$
L_c (i.e. the length of the converging section)	$\left(l\right)$
L_t (i.e. the length of the throat)	$\left(l\right)$
L_d (i.e. the length of the diffuser section)	$\left(l\right)$
e (i.e. the roughness of the wetted surface)	$\left(l\right)$
g (i.e. the gravitational constant)	$\left(l/t^2\right)$
P (i.e. the system pressure)	$\left(m/lt^2\right)$

That is for any function f_4 either the geometric terms can be included (not very practical) or they can be ignored and the resulting correlation from the data fit is applicable to the geometry of the meter/s that supplied the data set (which is in effect what has been universally done by all researchers so far).

Steven [2] dealt with the possibility of different fluid components separately as this significantly increases the complexity of the discussion and draws the research into an area largely uncharted in the publicly available literature. Whereas the gas composition is widely understood to have little to no effect on the performance of a wet gas flow DP meter (i.e. see Reader-Harris [5,6]) the same is not true for the liquid composition. Cazin [7], Reader Harris et al [5,6,8] and Steven et al [9,10] have shown that liquid properties can affect the performance of a DP meter with wet gas flow. A common industrial problem is the wet gas flow metering of a natural gas, hydrocarbon liquid and water flow mixtures. It was therefore useful to add to the dimensional analysis two different liquid properties:

$\dot{m}_w$ & $\dot{m}_{hl}$ (i.e. the water and hydrocarbon liquid mass flow rates respectively) (m/t)

ρ_w & ρ_{hl} (i.e. the water and hydrocarbon liquid densities respectively) (m/l^3)

μ_w & μ_{hl} (i.e. the water and hydrocarbon liquid viscosities respectively) (m/lt)

σ_w & σ_{hl} (i.e. the water and hydrocarbon liquid interfacial tensions respectively) (m/t^2)

This adds four extra parameters to the list and this therefore creates four extra dimensionless groups, i.e., we now get equation 16 in place of equation 15. The function f_5 must be determined experimentally:

$$\Delta P_{tp} = \frac{\dot{m}_g^2}{2\rho_g A^2} f_5\left(\frac{\dot{m}_w}{\dot{m}_g}, \frac{\dot{m}_{hl}}{\dot{m}_w}, \frac{\rho_w}{\rho_g}, \frac{\rho_{hl}}{\rho_w}, \frac{\mu_g D}{\dot{m}_g}, \frac{\mu_w D}{\dot{m}_g}, \frac{\mu_{hl}}{\mu_w}, \frac{\sigma_w \rho_g D^3}{\dot{m}_g^2}, \frac{\sigma_{hl}}{\sigma_w}, \frac{d}{D}, \frac{L_c}{D}, \frac{L_t}{D}, \frac{L_d}{D}, \frac{e}{D}, \frac{\rho_g^2 D^5 g}{\dot{m}_g^2}, \frac{P}{\rho_g U_{sg}^2}\right) \tag{16}$$

Note that the case of including two liquid components (f_5) significantly increases the complexity of the outcome compared to the case of one liquid component (f_1). It may be noticed that unlike equation 15, equation 16 has not been subsequently broken down to more recognizable dimensional groups. That is because, unlike the case of single liquid component wet gas flow, there is virtually nothing in the publicly available literature with regards to flow modeling a gas, water and hydrocarbon liquid flow mixture. There are no suggested dimensionless groups. There are a multiple of valid combinations of dimensionless groups that could be produced from manipulation of equation 16, but without extensive data analysis it is not possible to decide which, if any, would be the most useful. Such a project is beyond the scope of this technical paper. However, this paper will show that by varying the liquid properties between hydrocarbon liquid and water (i.e. varying the WLR), the Venturi meters differential pressure is affected. That is, the Venturi meters wet gas response is sensitive to this factor and hence the effects should be accounted for by the wet gas flow rate calculation procedures and some form of these dimensionless terms are therefore potentially important. It will also be shown that changing the orientation of the meter alters the meters performance with wet gas flow. This suggests that any correlation is only valid for set meter orientations.

5 THE HISTORY OF HORIZONTALLY INSTALLED DP METER WET GAS FLOW METERING DEVELOPMENT

The following review of DP meter wet gas meter research is based on horizontal flows. Very little published data on vertical flows exist.

In 1962 Murdock [11] published research into the effect two-phase / wet gas flow has on orifice plate meters. Murdock modeled a *stratified flow pattern* through the orifice meter and effectively suggested (using modern terminology here) that the over-reading was solely a function of the *Lockhart Martinelli parameter*. That is all geometric terms and other dimensionless groups listed in section 4 were not considered. For all other parameters held constant as the Lockhart Martinelli parameter increased the over-reading increased. That is:

$$OR = \frac{\dot{m}_{g\,Apparent}}{\dot{m}_g} = f\left(X_{LM}\right) = 1 + 1.26 X_{LM} \quad \text{--- (17)}$$

Note that in this paper the term " f " in the equations represents a non-defined function. This symbol is used several times. It does not represent the same function each time.

Between 1967-77 [12, 13] Chisholm developed Murdock's ideas regarding two-phase flow through orifice plate meters. Again Chisholm modeled *separated flow.* However, Chisholm considered the effect of the *Lockhart Martinelli parameter* and the *gas to liquid density ratio*. The geometric terms and the other dimensionless groups listed in section 4 were not considered. For all other parameters held constant an increasing gas to liquid density reduced the over-reading. Chisholm's equation is shown as equation set 18 (i.e. equations 18, 18a & 18b). Figure 5 shows this trend has since been shown true for Venturi meters (although Chisholm's orifice plate meter wet gas correlation is not appropriate for Venturi meters as although the trends are the same the actual over-reading values differ between DP meter designs.)

$$OR = \frac{\dot{m}_{g\,Apparent}}{\dot{m}_g} = f\left(X_{LM}, \frac{\rho_g}{\rho_l}\right) \quad \text{--- (18)}$$

i.e. $\dot{m}_g = \dfrac{\dot{m}_{g\,Apparent}}{\sqrt{1 + C X_{LM} + X_{LM}^2}}$ -- (18a) where $C = \left(\dfrac{\rho_g}{\rho_l}\right)^{\frac{1}{4}} + \left(\dfrac{\rho_l}{\rho_g}\right)^{\frac{1}{4}}$ --- (18b)

Note that the Lockhart Martinelli parameter (equation 6) includes a gas to liquid density term. However, Chisholm showed that the DP meter over-reading is not fully accounted for by the use of the Lockhart Martinelli parameter alone, and the correction is also dependent on a stand alone gas to liquid density term. There is a common misconception in fluid mechanics that if a dimensionless group is used in a correlation and it includes a particular parameter then the effect of that parameter is fully accounted for. It must be understood that this is not so. Inclusion of a parameter in one dimensionless group does not mean its effect is *fully* accounted for. The parameter may need to appear in other dimensionless groups. Chisholm's equation is a good example of this.

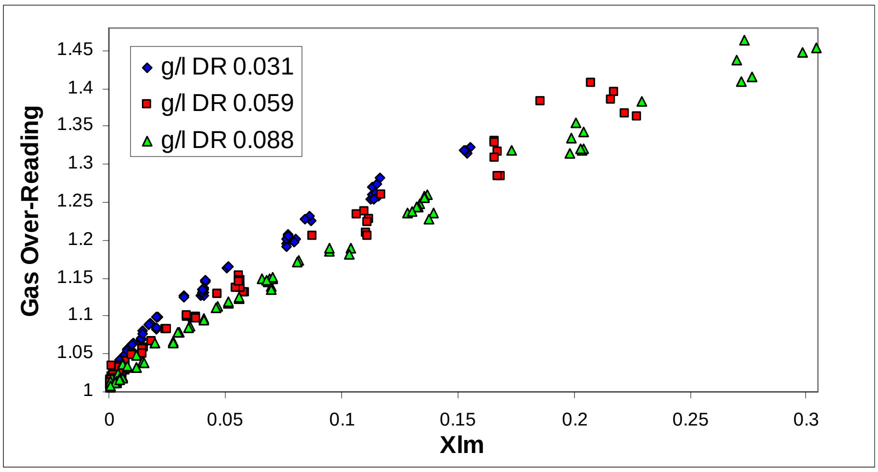

Fig 5. 6", 0.55 Beta Ratio Venturi Meter Wet Gas Data.

In 1997 de Leeuw [14] presented research into nitrogen / diesel oil wet gas flow through a 4", schedule 80, 0.4 beta ratio Venturi meter. In this seminal paper de Leeuw showed that the Venturi meter had the same wet gas flow trends as Murdock and Chisholm had shown for orifice plate meters. That is, the Venturi meter also had a wet gas response sensitive to the

Lockhart Martinelli parameter and the *gas to liquid density ratio*. However de Leeuw went further and showed a *gas densiometric Froude number* effect (see equation 19). For all other parameters held constant, as the gas densiometric Froude number increased from a very low value initially no effect was seen on the Venturi meter wet gas over-reading. At a critical value, further increases in the gas densiometric Froude number for all other parameters held constant increased the over-reading. De Leeuw's correlation is shown as equation set 19a, 20, 21a & 21b.

Note that the exponent "n" (in equation 19a) is commonly called the Chisholm exponent. Figure 6 shows a Venturi meter data set with the gas densiometric Froude number evident. De Leeuw [14] postulated that the reason was the influence of the flow pattern. At low gas densiometric Froude numbers the flow was *stratified*. As the gas densiometric Froude number increased the flow remained stratified and no gas densiometric Froude number effect was observed. However, with a further increasing gas densiometric Froude number the flow pattern transitions from *separated flow* to *annular mist flow*. As the gas

$$OR = \frac{\dot{m}_{g_{Apparent}}}{\dot{m}_g} = f\left(X_{LM}, \frac{\rho_g}{\rho_l}, Fr_g\right) \text{--- (19)}$$

$$\dot{m}_g = \frac{\dot{m}_{g_{Apparent}}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \text{--- (19a)} \quad \text{where} \quad C = \left(\frac{\rho_g}{\rho_l}\right)^n + \left(\frac{\rho_l}{\rho_g}\right)^n \text{--- (20)}$$

$$n = 0.606\{1 - \exp\{-0.746 Fr_g\}\} \text{---(21a) for } Fr_g \geq 1.5, \; n = 0.41 \text{---(21b) for } 0.5 \leq Fr_g < 1.5$$

densiometric Froude number continues to increase the percentage of liquid flowing in the annular ring reduces, the percentage of liquid flowing as droplets increases and the average droplet size reduces. As this happens the Venturi meters wet gas over-reading increases (towards the homogenous model). De Leeuw did not consider the geometric terms and other dimensionless groups listed in section 4.

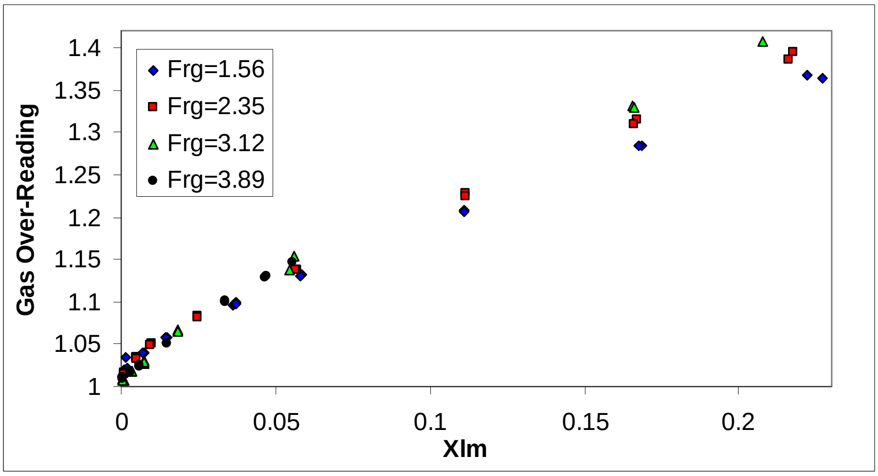

Fig 6. 6" 0.55 Beta Ratio Venturi Meter Wet Gas Data for 41 Bara / DR 0.059.

In 2005 Cazin et al [7] suggested if the flow pattern was known for an application the DP meter wet gas correlation could be modeled to that specific flow pattern. Cazin showed some success in applying the homogenous flow model to very high pressure and gas flow rate wet gas flows where homogenous flow is expected to exist. (Homogenous flow is defined as a two-phase flow where the phases are so well mixed the flow is effectively a pseudo-single phase flow.) In 2006 Steven [10] suggested a modification to the Cazin statement. In real applications it is not always practical to assume the flow pattern would be known or to assume one flow pattern will always exist through out the life time of the meter. It was postulated that the natural boundary condition for a DP meters wet gas response is the homogenous flow model. That is, as the gas dynamic pressure increases (which is caused by higher pressures and / or gas velocities) the flow pattern tends from stratified to homogenous flow and therefore a practical DP meter wet gas correlation should be flexible and also tend from a stratified flow model to the homogenous flow model. The homogenous model is shown as equation set 19a, 20 and 22.

$$\dot{m}_g = \frac{\dot{m}_{g_{Apparent}}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \quad \text{--- (19a)} \quad \text{where} \quad C = \left(\frac{\rho_g}{\rho_l}\right)^n + \left(\frac{\rho_l}{\rho_g}\right)^n \quad \text{--- (20)} \quad \& \quad n = \frac{1}{2} \quad \text{--- (22)}$$

In effect de Leeuw's early correlation partly follows this concept. De Leeuw had stated that for stratified flow (which for his meter size and flow condition range was gas densiometric Froude numbers less than 1.5) the over-reading was constant. As the flow pattern changed to annular mist the over-reading became a function of the gas densiometric Froude number. De Leeuw had the correlation becoming asymptotic to a Chisholm exponent of 0.606 (see equation 21a). This is clearly different to the homogenous models Chisholm exponent of 0.5. However, in 2007 Reader-Harris et al [8] postulated a reason for this. It was pointed out that in real applications the flow interacts with the DP meter and this can alter the flow pattern through the meter. Homogenous flow is an idealized concept and pipe flow which is effectively homogenized flow may not remain so as it interacts with the meter body. Hence, in real application it is possible for wet gas flow to be homogenous flow at the meter inlet but for the flow pattern to then be altered as it flows through the meter body. *Therefore, individual meter bodies may actually have characteristics where the Chisholm exponent is asymptotic to a value close to, but not necessarily precisely, a value of ½ as the gas dynamic pressure increases*. Let us call this real world boundary condition the *homogenous flow condition* to distinguish this reality from the idealized homogenous model.

In 2002 Stewart et al [15] showed that a wet gas flow DP meter *beta ratio* effect had been found for the cone type DP meter. In 2003 Stewart [16] showed the same effect for Venturi meters. For all other parameters equal, as the beta ratio of a DP meter increased the over-reading reduced. The beta ratio and gas densiometric Froude number effects have since been shown to also be true for orifice plate meters by Hall et al [17] and Stobie et al [18,19]. Therefore, the over-reading of a *set geometry* DP meter was known to be of the form of equation 23. Figure 7 shows Stewart's Venturi meter beta ratio effect data.

$$OR = \frac{\dot{m}_{g_{Apparent}}}{\dot{m}_g} = f\left(X_{LM}, \frac{\rho_g}{\rho_l}, Fr_g, \beta\right) \quad \text{-- (23)}$$

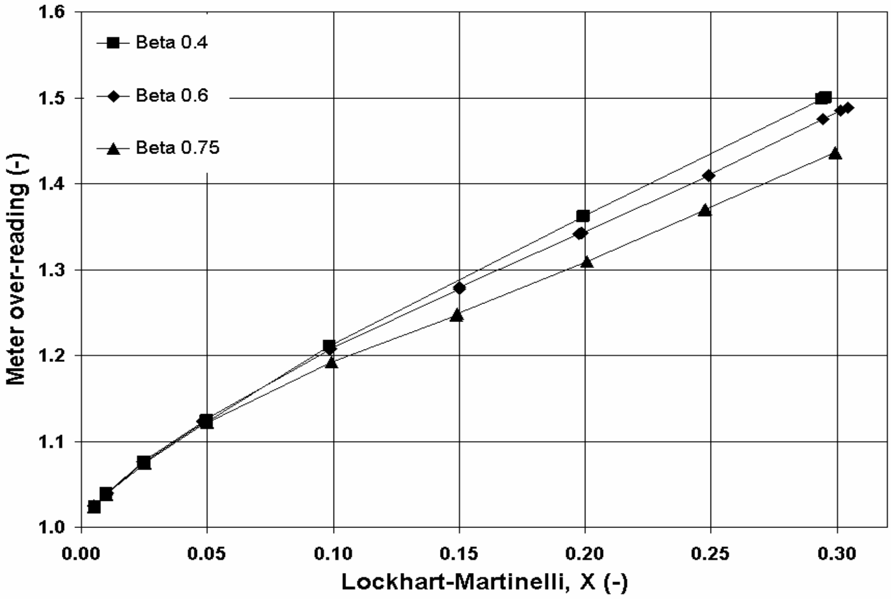

Fig 7. NEL 4", Venturi Meter Wet Gas Data for Nitrogen and Kerosene31 Bar(a), Fr_g=1.5

At the current time no beta ratio variable DP meter wet gas correlation has ever been produced. The existing correlations are set for use with a single beta ratio. The exception is for orifice plate meters where the effect is seen to exist but be weaker than other DP meter designs. The existing wet gas correlations can therefore be used without a beta ratio limit without incurring a significant increase in uncertainty. Note that the gas densiometric Froude number (equation 8) and the beta ratio include the diameter term ($\beta = d/D$). As stated earlier, the inclusion of a parameter in one or several dimensionless group does not necessarily fully account for the parameters effect on the system.

At this point of the research it was known different geometries (i.e. orifice, cone, Venturi meters etc.) produced different over-readings for the same wet gas flow conditions. Therefore, data fits " f " to each different geometry were different to each other.

In 2005 Cazin et al [7] stated a liquid property effect on DP meter wet gas over-readings existed. In 2006 Steven [9,10] and Reader-Harris [5,6] independently showed a liquid property effect. For the case of all other parameters held constant, a wet gas flow with water sometimes had a smaller over-reading than if the liquid was a light hydrocarbon liquid. Reader-Harris et al [5,6] also indicated that the gas type has no significant effect on a DP meters wet gas over-reading. Figure 8 reproduces a sample of the Reader-Harris results. Steven's conjecture [10] was that the liquid properties of surface tension and viscosity made it necessary for a larger gas dynamic force to be applied to a given wet gas flow with water than would be required for the same wet gas flow with light hydrocarbon liquid for the flow pattern to be shifted from stratified to annular mist flow. That is, as flow pattern change was regarded as the reason for a DP meters shift of over-reading, it was the waters relatively high resistance to changing from stratified to annular mist flow compared to light hydrocarbon liquids that caused the difference. The viscosity and / or surface tension were therefore shown to be important. When considering the resistance of a liquid to being changed from a stratified to an annular mist wet gas flow it is generally believed surface tension is the dominant parameter over viscosity. The generic DP meter wet gas flow correlation was now thought to be of the form shown as equation 24. However, no wet gas flow correlation for any DP meter is known to have been published that includes liquid property effects and no work has been published on which dimensionless groups should be used to quantify the liquid property effect. Those shown in equation 24 are an example of one possibility only. Equation 24 still assumes the data fit " f " is going to be for a set geometry (i.e. meter size), the liquid is one component and the meter is installed in one set orientation.

$$OR = \frac{\dot{m}_{g_{Apparent}}}{\dot{m}_g} = f\left(X_{LM}, \frac{\rho_g}{\rho_l}, Fr_g, \beta, \mathrm{Re}_{sg}, \mathrm{Re}_{sl}, We_{tp} \right) \quad \text{-- (24)}$$

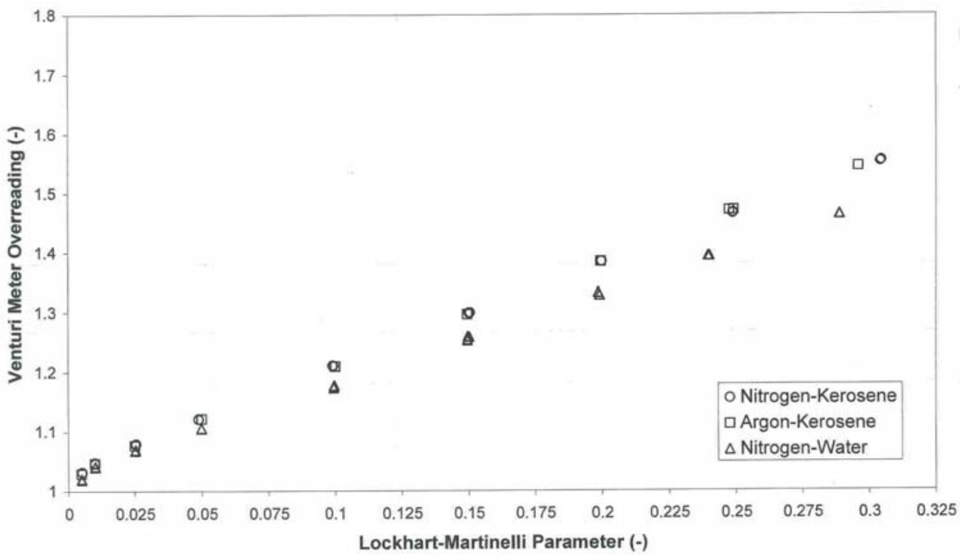

Fig 8. 4", 0.75 Beta Ratio Venturi Meter, DR 0.046, Gas Densiometric Froude Number of 2.5.

Cazin et al [7] stated that liquid mixtures of water and hydrocarbon liquid had a complex relationship with the DP meter wet gas over-reading. It was stated that at a WLR of 60%, for all other parameters held constant there was a discontinuity in the over-reading. It was postulated by Cazin et al that this was the boundary between water continuous and hydrocarbon liquid continuous wet gas flows. Steven et al [10] independently confirmed the Cazin et al [7] results that showed wet gas flow with a liquid consisting of water and hydrocarbon liquid gave over-readings of the same general magnitude as when the liquid was either water or hydrocarbon liquid only. However, nothing was said about the precise relationship of the WLR to the DP meter over-reading. Figure 9 shows the CEESI 2" Venturi wet gas results.

Only two comments are known to the authors to be in the literature regarding a possible diameter effect. In 2005 Cazin et al [7] compared various DP meter wet gas flow correlation performances to 2", 4" and 6" Venturi meter wet gas data sets from different test facilities. Individual correlations had different results for different diameter meters. However, there were other variables and diameter effect was not Cazin's primary research aim. The topic was passed with a question on diameter effects remaining open. In 2006 Steven [9] showed a comparison between the wet gas over-reading results for horizontally installed CEESI 2" and

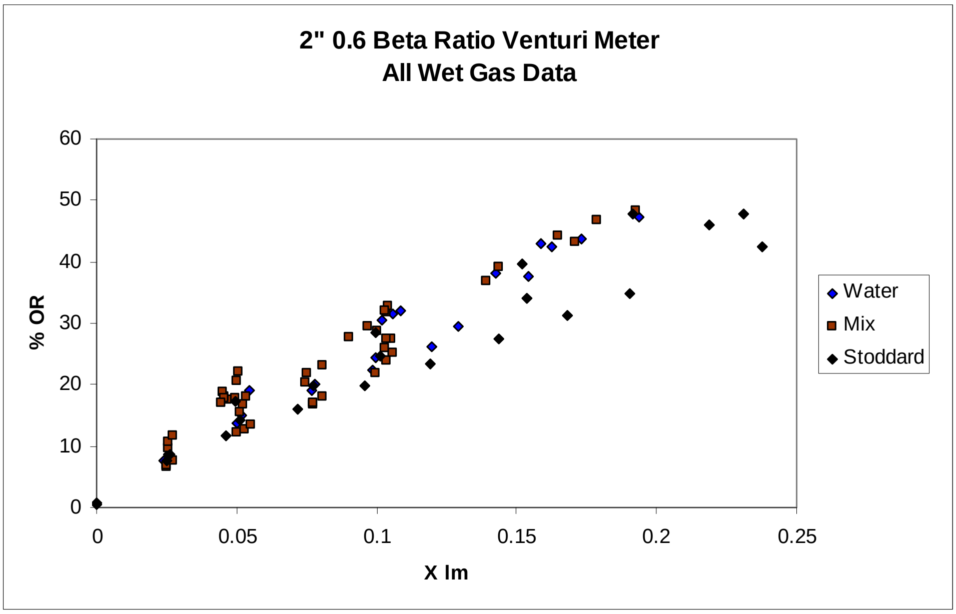

Fig 9. CEESI 2" 0.6 Beta Ratio Venturi Meter Wet Gas Flow Data with Various Liquid Components.

NEL 4", 0.6 beta ratio Venturi meters with similar fluids and similar Lockhart Martinelli parameter, gas to liquid density ratio and gas densiometric Froude number ranges. The 2" data was from a CEESI multiphase wet gas flow test loop (running in two-phase mode). The 4" data was from a NEL two-phase wet gas flow test loop. The smaller meter seemed to have a lower over-reading. The graph is reproduced here as Figure 10. This is not enough evidence to make any firm statement regarding a generic DP meters wet gas flow diameter effect.

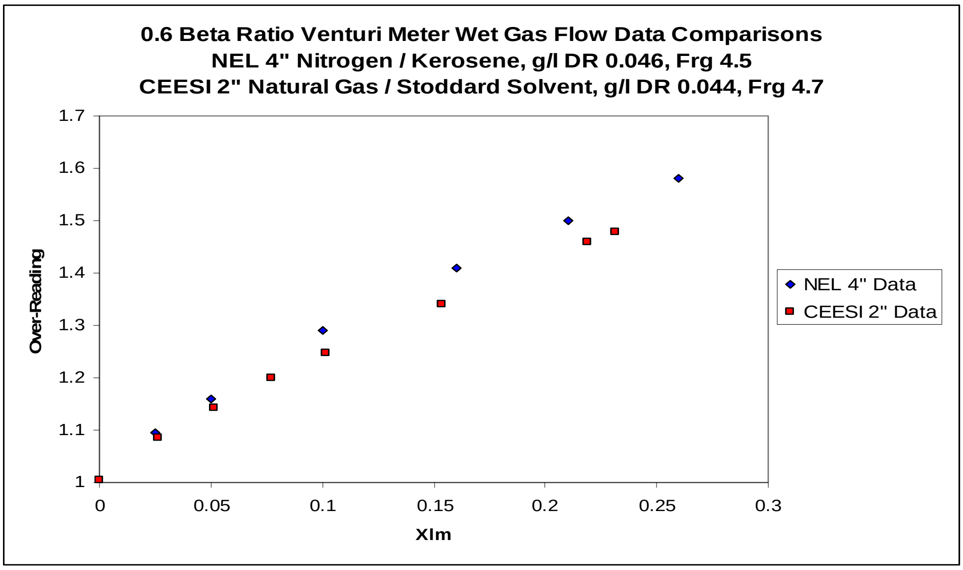

Fig 10. CEESI 2' / NEL 4", 0.6 Beta Ratio, Venturi Meter Wet Gas Response

Cazin et al [7] discussed some low pressure, low flow rate data on vertical down flow. However, no work is known to the authors to have been publicly released regarding investigating the generic response of a DP meter when the orientation is changed from horizontal to vertically up. There is therefore little publicly available evidence to state if a correlation formed from horizontal orientated DP meters can be applied to vertical up (or any other orientated) flow meters. As the flow patterns can be significantly affected by orientation (see section 3) and the horizontal test data evidence seems to suggest the flow pattern dictates the generic DP meters over-reading it seems that horizontal data based wet gas correlations should not be used for other meter orientations. However, there is little data to confirm this.

6 NEW CEESI DATA AND PRELIMINARY INVESTIGATIONS REGARDING DIAMETER, WLR AND ORIENTATION ISSUES

In 2004 CEESI commissioned a 2", schedule 80, wet gas multiphase flow loop that flowed natural gas, (fresh) water and Stoddard solvent (C9-C12) between 12 and 75 bar and between 5 and 25 m/s. In 2006 CEESI superseded this system with a nominally 4", schedule 80, wet gas multiphase flow loop that flows natural gas, (fresh) water and kerosene between 12 and 75 bar and between 5 and 25 m/s. Test sections can be orientated in any way, e.g. horizontally or vertically up or down. During commissioning of each system 2" and 4", 0.6 beta ratio ISO compliant Venturi meters were tested respectively. (The 2" meter had a 6^0 diffuser half angle while the 4" meter had a 7^0 diffuser half angle.) The aim of each flow run was to commission the test system, not to do wet gas flow DP meter research. However, there is some value in the data sets with respect to the Venturi WLR response and in comparisons of the different diameter meters response. In September 2008 CEESI carried out a small test series to gain more data on the diameter comparison and get some preliminary vertical up data comparable with horizontal data. The following sections discuss some results of the preliminary analysis.

6.1 The 4", 0.6 Beta Ratio Venturi Meter Wet Gas Response to Various Liquid Properties

Figure 11 shows CEESI multiphase wet gas loop commissioning data for the 4", schedule 80, 0.6 beta ratio Venturi meter. The data set shown in Figure 11 is for the natural gas, water and kerosene mixture range of flows only. It is immediately noticeable that the data looks similar to the other data sets shown earlier. An increasing Lockhart Martinelli parameter produces an increasing over-reading. The higher the gas to liquid density ratio the lower the over-reading for a range of WLR values but otherwise set flow conditions. (Note that the gas to liquid density ratio and gas densiometric Froude number values are averaged for each point shown but they represent a range of data around each of these nominal values.) In order to investigate liquid property effect further the data for the natural gas and kerosene (or hydrocarbon liquid, i.e. "HCL") flow only was first isolated and analyzed alone as this situation is familiar to researchers and would confirm the correct operation of the system. Once this was done analysis of the other data could take place.

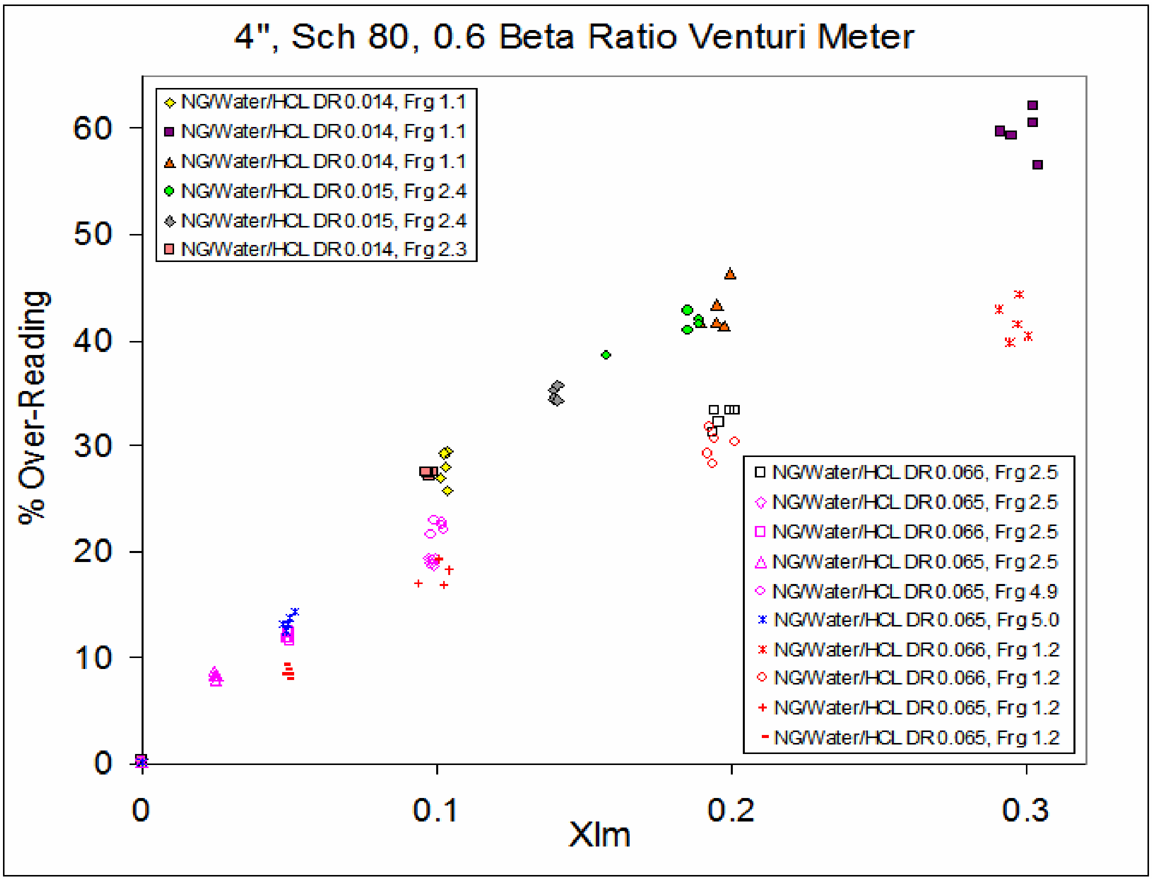

Fig. 11. CEESI Multiphase Wet Gas Flow Test Facility Horizontally 4”, 0.6 Beta Venturi Data.

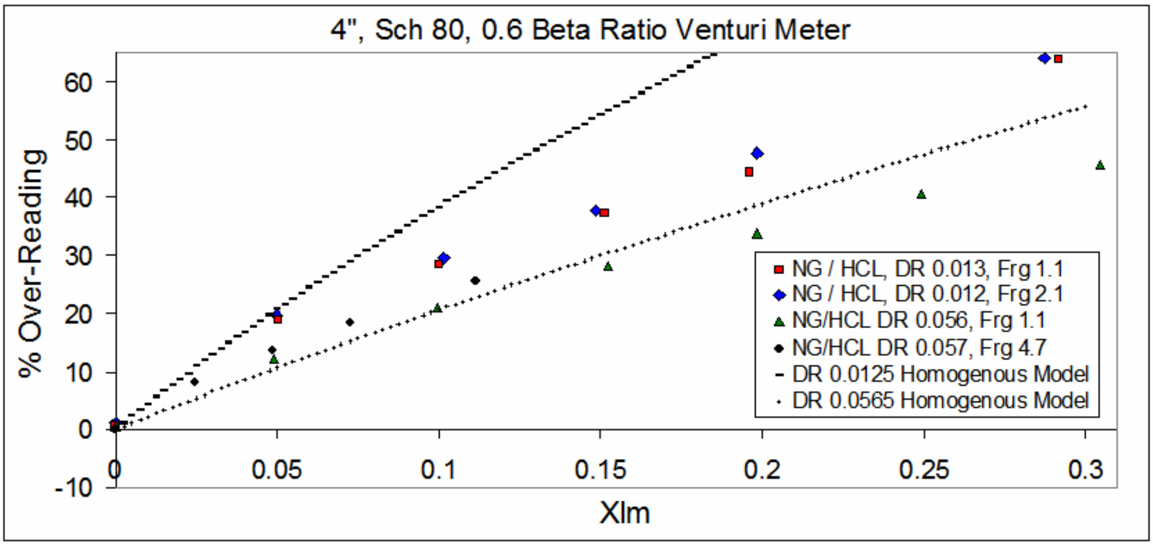

Fig 12. CEESI 4”, 0.6 Beta Ratio Venturi Meter Natural Gas / Kerosene Data.

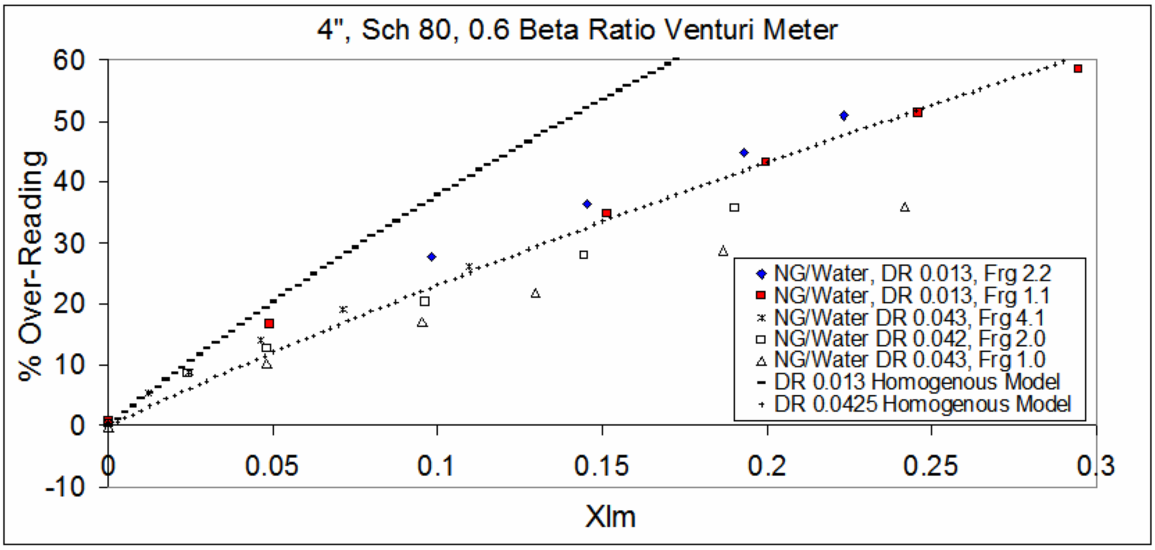

Fig 13. CEESI 4", 0.6 Beta Ratio Venturi Meter Natural Gas / Water Data.

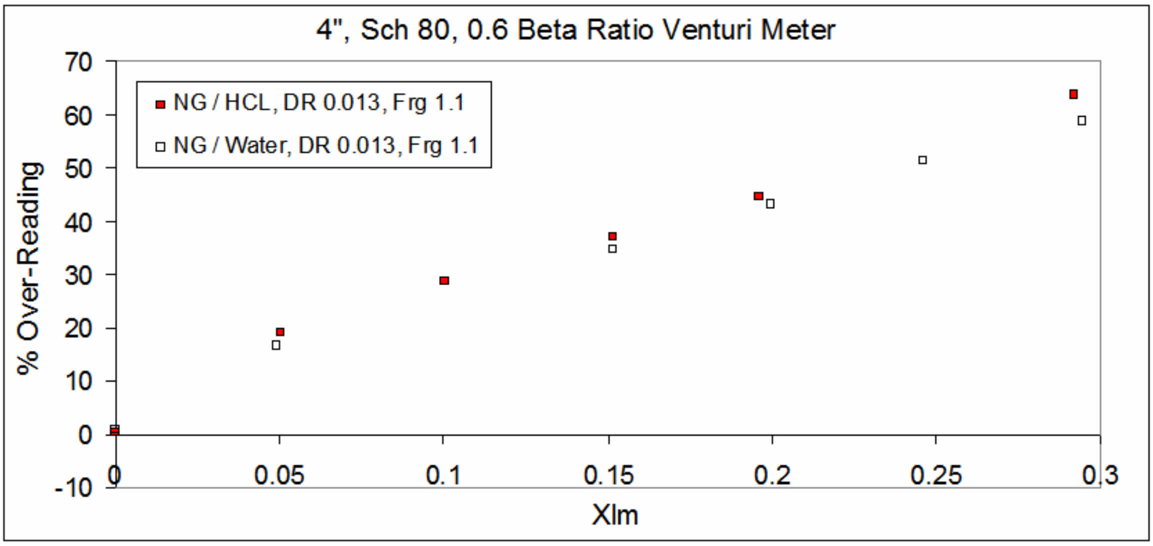

Fig 14. CEESI Low Pressure, Low Gas Flow Rate Data Comparing Kerosene to Water.

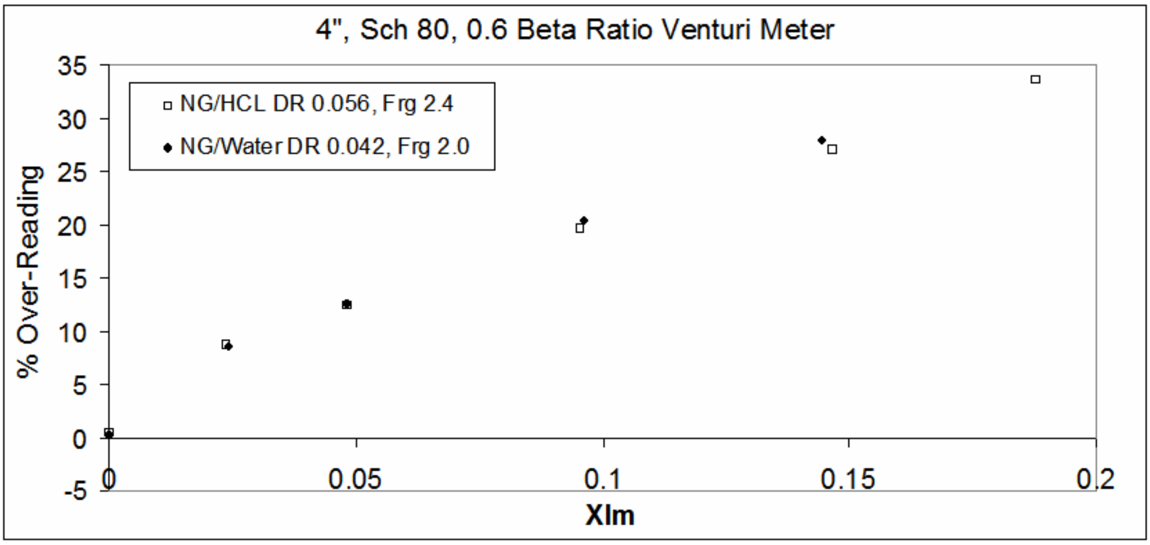

Fig 15. CEESI Moderate Pressure, Moderate Gas Flow Rate Data Comparing Kerosene to Water.

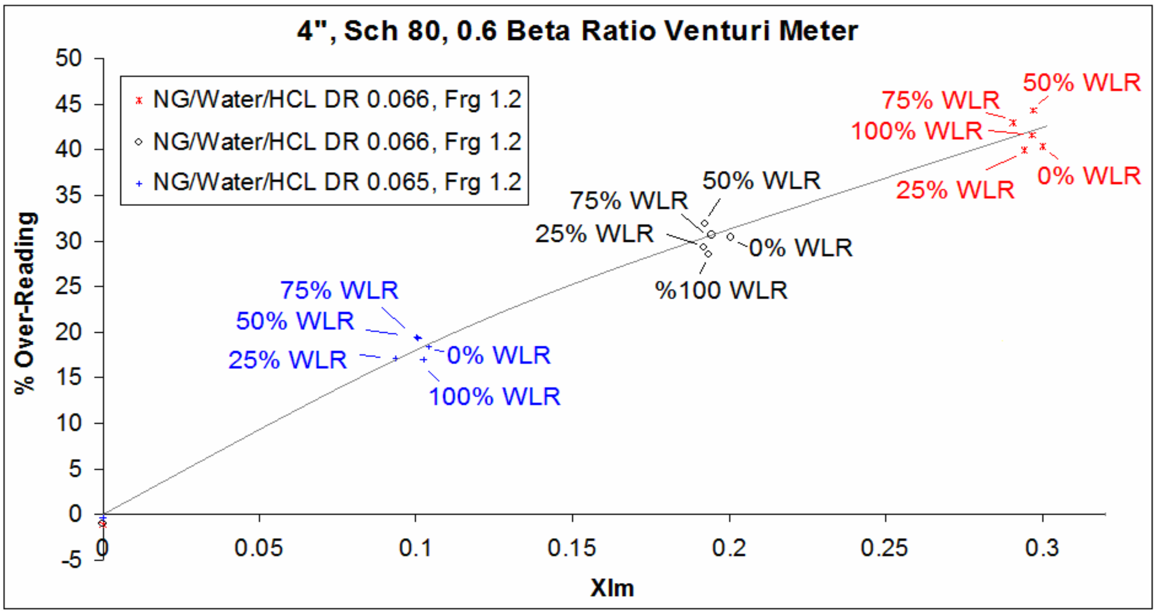

Fig 16. Sample CEESI Natural Gas / Water / Kerosene Mixture Data with Sketched Approximate OR Line.

Figure 12 shows the natural gas / kerosene flow data only. Note that the gas to liquid density ratio effect is evident. Also for the separated gas to liquid density ratio values the gas densiometric Froude number effect is evident. That is, for a set gas to liquid density ratio as the gas densiometric Froude number increases the over-reading increases.

Note that the two nominally set gas to liquid density ratios have the respective homogenous model predictions shown in Figure 12. The low gas to liquid density ratio data is seen to be well below the homogenous model. The moderate gas to liquid density ratio data is seen to straddle the homogenous model. This is a typical result. As liquid is driven by the gas dynamic pressure, for otherwise set conditions, when increasing gas density (i.e. increasing the gas to liquid density ratio) the gas dynamic pressure is increased therefore increasing the driving force on the liquid phase. Likewise, for otherwise set conditions when increasing the gas velocity (i.e. the gas densiometric Froude number) the gas dynamic pressure is increased therefore increasing the driving force on the liquid phase. That is, as the gas dynamic pressure increases the DP meters wet gas flow response tends to the homogenous flow *condition*. The approach to the meters homogenous flow condition is asymptotic. This means that for a given wet gas flow, as the gas dynamic pressure increases by constant step amounts (by changing the gas pressure and / or the gas

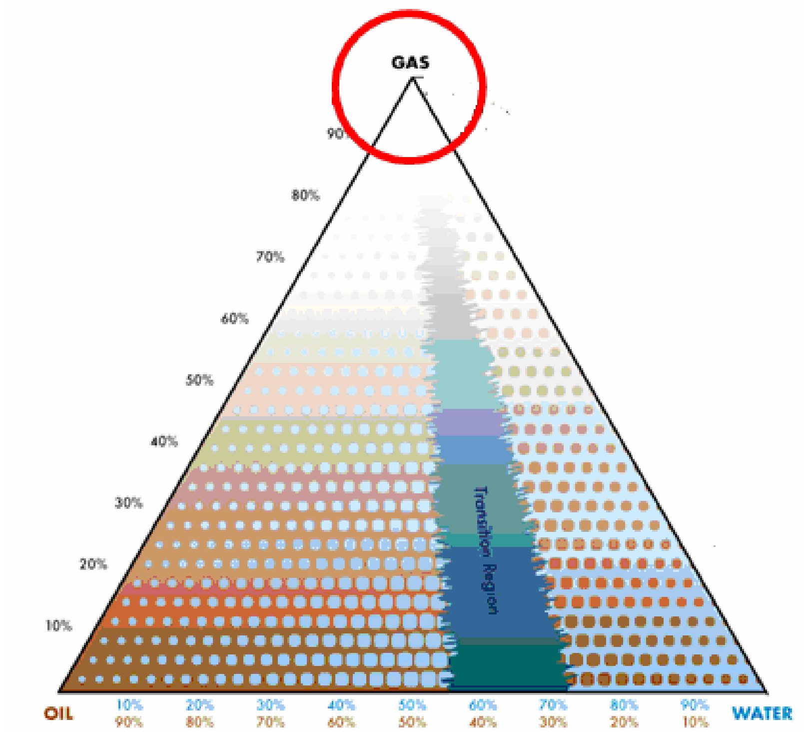

Fig 17. Jamieson's Multiphase Flow Triangle [20].

velocity) the step change of over-reading diminishes. For a set Lockhart Martinelli parameter, as the gas to liquid density ratio increases a given range of gas densiometric Froude numbers produces less of a spread of over-readings. As the inlet flow reaches homogenous flow the gas densiometric Froude number effect on the over-reading has diminished to the point where it has disappeared. For example, at the low gas to liquid density ratio value of 0.013 and low gas densiometric Froude number value of 1.1 the flow is stratified. Increasing the gas densiometric Froude number to a value of 2.1 shifts the flow towards annular-mist flow and hence the homogenous flow condition. However, for the wet gas flow with the much higher gas to liquid density ratio value of 0.056, the low gas densiometric Froude number value of 1.1 still has a much larger gas dynamic pressure and the data is close to the homogenous flow condition. Increasing the gas densiometric Froude number to a value of 4.7 increases the meters wet gas over-reading to slightly above the homogenous model (suggesting the homogenous flow condition is indeed slightly different so the meter body is influencing the local flow pattern). However, the difference in over-reading between the two gas densiometric Froude numbers is relatively small.

Figure 13 shows the CEESI 4", schedule 80, 0.6 beta ratio Venturi meters response to natural gas and water flows only. It is evident the same trends exist here as did when the liquid was kerosene. Again the same gas to liquid density ratio and gas densiometric Froude number trends are seen, as is the data's relationship with the homogenous model predictions. This is independent verification of Reader Harris [6] claim that Venturi meters have the same wet gas *trends* for gas / light hydrocarbon liquid and gas / water flows.

Figure 14 shows natural gas / water and natural gas / kerosene flow data for low gas to liquid density ratio and low gas densiometric Froude numbers. Both flows were confirmed via the systems view port to be similar stratified flows. The Venturi meter was therefore found to behave in a similar way for similar flow patterns regardless of the different liquid types. Again, this is independent verification of the Reader Harris [6] claims.

Figure 15 shows natural gas / water and natural gas / kerosene flow data for higher gas to liquid density ratio and gas densiometric Froude number values. Both flows were confirmed via the systems view port to have some form of annular mist flow patterns. As the test matrix was not designed for Venturi meter wet gas flow research there were no directly equivalent flow conditions for gas / water and l gas / kerosene flows. We would like to plot similar set gas to liquid density ratio and gas densiometric Froude number values for each of the l gas / water and gas / kerosene flows and look for differences in over-reading. As this is not possible another less direct data analysis technique must be utilized.

It is possible to plot similar over-readings and show that the conditions that caused these results were from different flow conditions. This infers that there is an effect. In Figure 15 we see the over-readings for a flow of natural gas / water at a gas to liquid density ratio of 0.056 and gas densiometric Froude number of 2.4. This data shows approximately the same over-reading as a flow of natural gas / kerosene at a gas to liquid density ratio of 0.042 and gas densiometric Froude number of 2.0. The gas to liquid density ratio percentage difference is -25% and the gas densiometric Froude number difference is -17%. By the authors experience, by examining various DP meter wet gas correlations and by the evidence in Figures 12 & 13 it is known that a Venturi meters wet gas flow response is more sensitive to the gas to liquid density ratio than the gas densiometric Froude number. This coupled with the fact that the liquid to gas density ratio difference is proportionally greater than the gas densiometric Froude number difference strongly suggests that the gas to liquid density ratio effect should dominate the gas densiometric Froude number in this data set. Examining Figure 15 shows that the much lower gas to liquid density ratio (0.042) of the gas / water flow has the same over-reading as the higher gas to liquid density ratio (0.056) of the gas / kerosene flow. This difference can not be explained by the relatively small difference in the gas densiometric Froude numbers. Something else must be causing the gas / water flow to be giving a lower over-reading than the gas / kerosene flow would at those same conditions. The likely answer is the liquid properties. That is, the gas / water wet gas flow has a lower over-reading than the gas / kerosene flow at the same conditions. This suggests that a gas / water wet gas flow tends to be more stratified than a gas / kerosene flow for set gas to liquid density ratio and gas densiometric Froude numbers. This result independently backs the claims of Reader-Harris [6].

Figure 16 shows a selection of natural gas / water / kerosene wet gas flow data. When holding constant thermodynamic conditions (i.e. pressure and temperature) it is not possible to keep all wet gas flow parameters equivalent when varying the WLR. That is, if a flow has a particular Lockhart Martinelli parameter, gas to liquid density ratio and gas densiometric Froude number and the WLR is altered, then, this also alters the gas to liquid density ratio and gas densiometric Froude number. As the aim of this test matrix was the commissioning of the wet gas test facility only an approximate attempt to group data was made. The conditions stated in the legend of Figure 16 are therefore nominal only and actual individual values can vary by a few percent. Nevertheless, on close inspection, the results in Figure 16 seem to show some interesting Venturi meter wet gas flow behaviour. A general trend appears to exist where the data at WLR values of 50% and 75% seem to have the highest over-reading. If we start with a gas / kerosene flow only (i.e. a WLR of 0%) and then, for nominally constant Lockhart Martinelli parameter, gas to liquid density ratio and gas densiometric Froude number values, increase the WLR, then the 25% WLR result is very similar to the 0% WLR result. (When examining Figure 16 remember to take into account that the Lockhart Martinelli parameter values are varying. This largely accounts for the illusion that 25%WLR has a lower over-reading than 0% WLR.) By 50% the over-reading seems to have increased. However by 75% WLR the over-reading seems to be reducing again and 100% WLR is lower again. That is, something changes between 50% and 75% WLR to cause the over-reading / WLR trend to reverse. It is noteworthy here that Cazin [7] stated a discontinuity was found at 60% WLR in earlier independent Venturi meter wet gas tests. Cazin postulated that this discontinuity coincided with a possible inversion region where the liquid phase changes from hydrocarbon liquid continuous to water continuous flow. Furthermore, Jamieson [20] indicated that in general multiphase flow (i.e. flows of gas / oil and water) the inversion point was approximately between 55% and 70%. The Jamieson triangle is reproduced here as Figure 17.

Whatever the reason for the Venturi meters wet gas flow response to varying WLR values it appears on close inspection that the response is not linear. A linear response is assumed when the water / hydrocarbon liquid mix is treated as a homogenous liquid phase (e.g. when averaging the liquid density in equation 11 & 12). Unfortunately these authors can not at the time of writing offer any practical alternative to this simple (if technically flawed) approach.

Thankfully, the Venturi meters wet gas flow over-reading sensitivity to WLR is not as significant as its sensitivity to the Lockhart Martinelli or gas to liquid density ratio, so for practical solutions engineers can get approximate over-reading estimations by using this imperfect liquid property averaging technique.

6.2 Comparisons of the 2" & 4", 0.6 Beta Ratio Venturi Meter Wet Gas Responses

Due to lack of alternatives (or in some cases ignorance of the potential problem) industry currently tends to apply published wet gas flow DP meter correlations for one meter geometry on other meter geometries. A common extrapolation of a DP meter wet gas correlation is therefore applying it to meter sizes out with its scope.

The single direct meter size comparison known by the authors to be in existence was shown here as Figure 10. This suggested that there may be a wet gas flow DP meter diameter effect. This Figure shows that at a relatively high gas to liquid density ratio (approximately 0.045) and gas densiometric Froude number (approximately 4.6) for gas and light hydrocarbon liquid at least, the smaller meter has a smaller over-reading. Therefore CEESI carried out further research. The 4" and 2" , 0.6 beta ratio horizontally installed Venturi meters tested at CEESI with natural gas and hydrocarbon liquid only and then natural gas and water only had their data sets inter-compared searching for a diameter effect. For set liquids, pairs of gas to liquid density ratios and gas densiometric Froude numbers were plotted together on a Murdock plot (i.e. Lockhart-Martinelli parameter vs. over-reading). The results are shown in Figures 18 to 23.

The results were not as expected. For the majority of the comparisons no significant meter size / diameter / scaling effect could be seen. For all the gas / light hydrocarbon liquid data across all data ranges tested the diameter seemed to have no significant effect on the wet gas over-reading (see figures 18 to 20). The same was true for the first two gas / water flow data comparisons (see Figures 21 and 22). However, the final data set comparison was between gas / water flows at a moderate gas to liquid density ratio (approximately 0.035) and a relatively high gas densiometric Froude number (approximately 4.1). This data set contradicted the other five comparisons (see Figure 23) and agreed with the earlier research which stated that the smaller meter has the smaller over-reading. To confuse matters further, the new data for gas / light hydrocarbon liquid flow at moderate gas to liquid density ratio (approximately 0.045) and a relatively high gas densiometric Froude number (approximately 4.7) is a very close match to the earlier released comparison (Figure 10) but it does not show the same significant diameter effect. However, it is noteworthy that this particular data comparison has a 4" meter maximum Lockhart Martinelli parameter of 0.12. There is a hint the data sets are beginning to diverge such that the smaller meter has a slightly smaller over-reading at higher Lockhart Martinelli parameter values (see Figure 20). However, even such an extrapolation does not give the size of over-reading difference shown in Figure 10. Therefore, unfortunately the results of this research are inconclusive.

With modern wet gas flow DP meter correlations tending to be each for a set meter geometry (including a set beta ratio), and one fluid type combination they are typically of the form:

$$OR = \frac{\dot{m}_{g_{Apparent}}}{\dot{m}_g} = f\left(X_{LM}, \frac{\rho_g}{\rho_l}, Fr_g\right) \text{--- (19)}$$

As all evidence points to the flow pattern having a critical role in dictating the DP meter over-reading, the application of such a correlation to different meter sizes is therefore the same as assuming that the diameter difference makes no difference to the flow patterns the pipe experiences for a set group of Lockhart Martinelli parameter, gas to liquid density ratio and gas densiometric Froude number values. Let us now investigate what changing a diameter for these set values actually does to the predicted flow pattern.

Let D_1 be the diameter of a small pipe and D_2 be the diameter of a large pipe. Therefore $D_1 < D_2$. Now let us consider that the two meters have the same fluids flowing through them and the flows are at the same pressures and temperatures. We therefore know that the gas and liquid densities are the same for both cases. Therefore, through out the following argument the gas to liquid density ratio is the same for both meters. Now if we equate each of the two different diameter case parameters we get the following results.

a) For the equal gas to liquid density ratio, for the matching Lockhart Martinelli parameters we get:

$$\left(\frac{\dot{m}_l}{\dot{m}_g}\right)_{D_1} = \left(\frac{\dot{m}_l}{\dot{m}_g}\right)_{D_2} \quad \text{---- (25)}$$

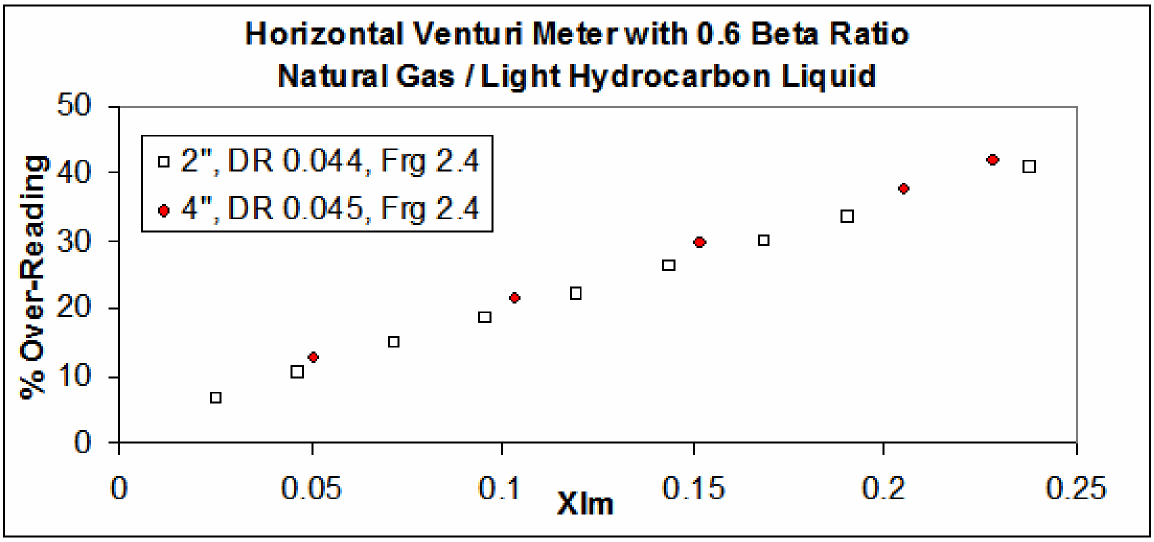

Fig 18. Diameter Comparisons for Gas / Kerosene Moderate Pressure, Moderate Gas Flow Rate Data.

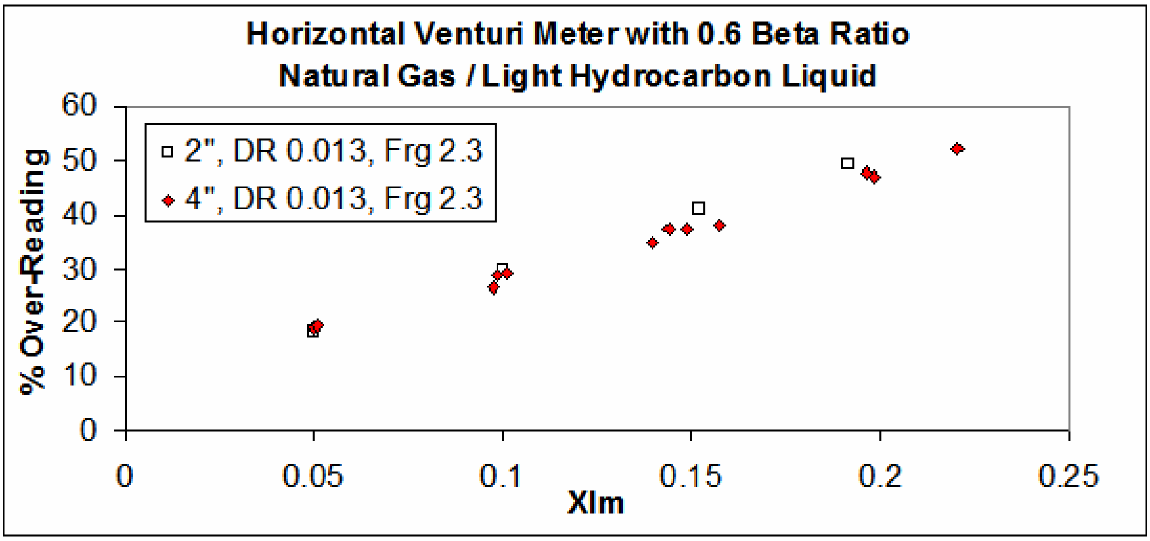

Fig 19. Diameter Comparisons for Gas / Kerosene Low Pressure, Moderate Gas Flow Rate Data.

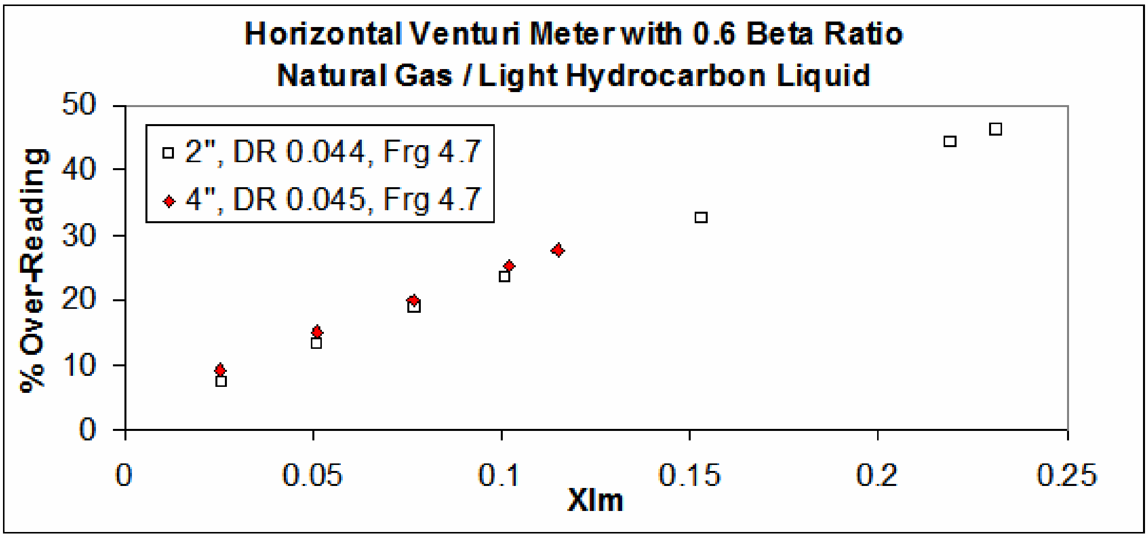

Fig 20. Diameter Comparisons for Gas / Kerosene Moderate Pressure, High Gas Flow Rate Data.

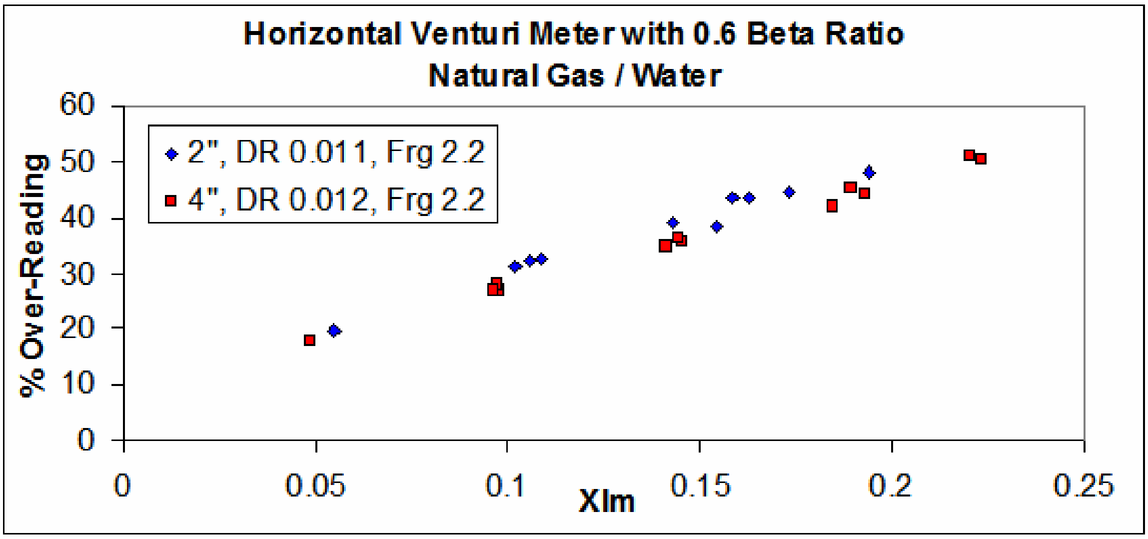

Fig 21. Diameter Comparisons for Gas / Water Low Pressure, Moderate Gas Flow Rate Data.

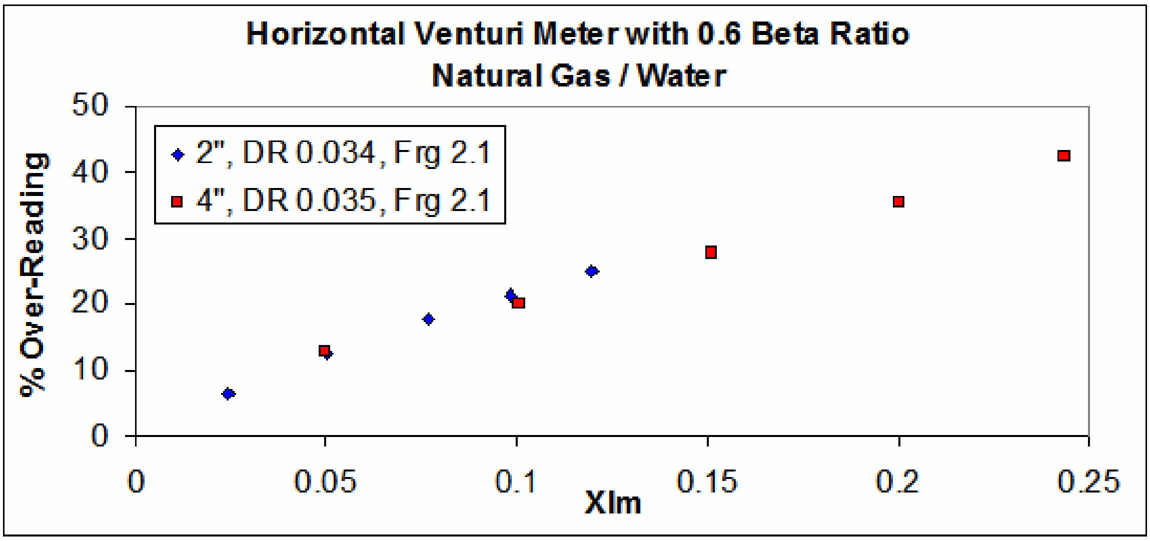

Fig 22. Diameter Comparisons for Gas / Water Moderate Pressure, Moderate Gas Flow Rate Data.

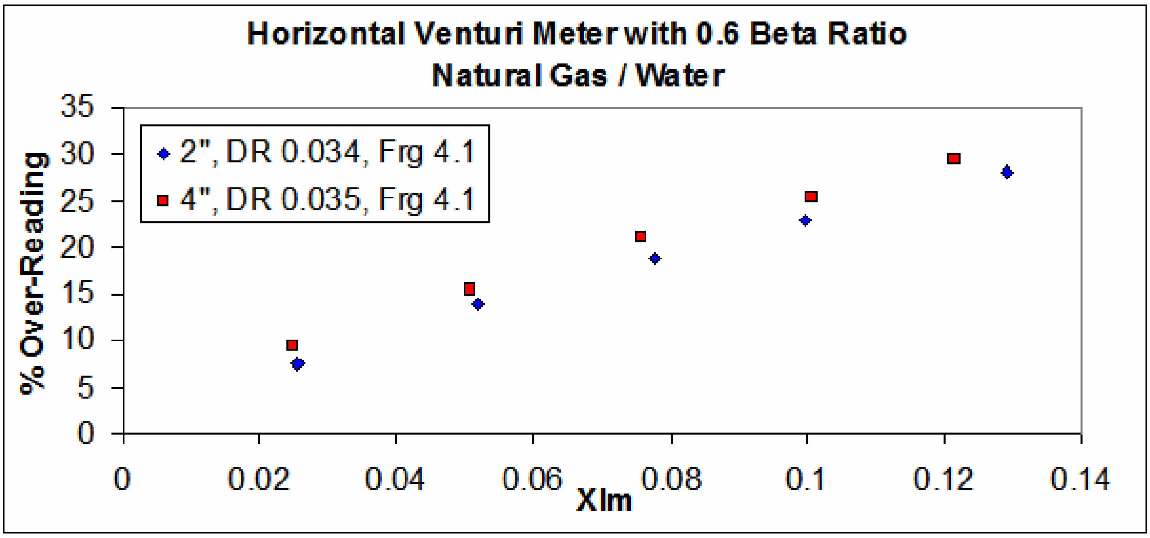

Fig 23. Diameter Comparisons for Gas / Water Moderate Pressure, High Gas Flow Rate Data.

where subscripts D_1 and D_2 represent the small and large diameter meters respectively. Now from mass continuity we have:

$$\dot{m}_g = \rho_g A U_{sg} \text{ ---- (26a)} \quad \text{and} \quad \dot{m}_l = \rho_l A U_{sl} \text{ ---- (26b)}$$

Therefore, for each diameter meter, we can substitute equations 26a and 26b into equation 25 to get:

$$\left(\frac{\rho_l A U_{sl}}{\rho_g A U_{sg}} \right)_{D_1} = \left(\frac{\rho_l A U_{sl}}{\rho_g A U_{sg}} \right)_{D_2} \quad \text{--- (25a)}$$

where the areas and superficial phase velocities inside each bracket are for that meter size only. Now, as the areas on the numerators and denominators of equation 25a for the respective meters are by definition the same (even though they are not the same on either side of the equation), and as we have a single set gas to liquid density ratio equation 25a can be reduced to:

$$\left(\frac{U_{sl}}{U_{sg}} \right)_{D_1} = \left(\frac{U_{sl}}{U_{sg}} \right)_{D_2} \quad \text{--- (25b)}$$

For the matching gas densiometric Froude number parameters at the set gas to liquid density ratio we get:

$$\left(\frac{U_{sg}}{\sqrt{D_1}} \right)_{D_1} = \left(\frac{U_{sg}}{\sqrt{D_2}} \right)_{D_2} \quad \text{--- (26)}$$

Rearranging:

$$\left(U_{sg} \right)_{D_1} = \left(U_{sg} \right)_{D_2} \sqrt{\frac{D_1}{D_2}} \quad \text{--- (26a)}$$

Now, as we earlier set $D_1 < D_2$ we see from equation 26a that:

$$\left(U_{sg}\right)_{D_1} < \left(U_{sg}\right)_{D_2} \quad \text{-- (27a)}$$

Now, equation 25b when combined with equation 27a also shows that:

$$\left(U_{sl}\right)_{D_1} < \left(U_{sl}\right)_{D_2} \quad \text{--- (27b)}$$

Therefore, setting the Lockhart Martinelli parameter, gas to liquid density ratio and gas densiometric Froude number values for different pipe diameters means the superficial gas and liquid velocities reduce as the pipe diameter reduces. That means, for set Lockhart Martinelli parameter, gas to liquid density ratio and gas densiometric Froude number values as the pipe diameter reduces the flow condition tends to the origin of the Taitel & Dukler flow pattern maps (see Figures 2, 3a & 3b) and therefore tend towards the stratified region from the annular mist region. However, Taitel & Dukler [4] suggested that holding the superficial gas and liquid velocities constant and reducing the pipe diameter shifts the border between stratified and annular mist flows (e.g. see Figures 3a & 3b). So as the pipe diameter reduces the border of these flow patterns also approaches the origin of the Tailtel & Dukler flow pattern map. That is, for all other parameters held constant Taitel & Dukler claim reducing the pipe diameter promotes annular mist flow. These are apposing trends. The reducing pipe diameter for the above set wet gas flow parameters, produces smaller superficial gas and liquid velocities, but as this trend promotes stratification of the flow pattern the pipe diameter effect itself is promoting annular mist flow. It is therefore possible for the data sets shown here that the trends have largely cancelled each other out. That is not to say that these trends will *always* cancel each other out regardless of the two meter diameters and flow conditions being considered. There is no proof that these trend will always be equal and opposite. More tests on a wider range of pipe diameter ranges and flow rate conditions are required before a definitive pipe diameter result is obtained.

6.3 Comparisons of the 4”, 0.6 Beta Ratio Venturi Meter Horizontal & Vertical Up Wet Gas Responses

Extrapolation of existing wet gas flow horizontally installed DP meter correlations for use with other diameters is not the only extrapolation that is known to be done in real world applications. DP meters can be installed in vertical up wet gas flows. However, if this is done there is the question of whether the horizontal wet gas flow DP meter data sets (and hence correlations) are applicable to this situation. As it is known that the flow pattern dictates the horizontally installed DP meter wet gas flow response it is reasonable to assume the vertical up flow pattern will dictate the vertically up installed DP meters wet gas response.

In section 3 the differences in the horizontal and vertically up flow patterns were discussed. Low gas dynamic pressures cause instable churn flow while higher gas dynamic pressures produce annular mist flow that is symmetrical. Horizontal annular mist flow is only effectively symmetrical at very high gas dynamic flow rates when the liquids weight is much less than the gas dynamic driving force on the liquid. There is therefore a subtle difference between vertical up and horizontal annular mist flows. For a given annular mist flow condition the vertical flow will always be a little closer to homogenous flow in as much as it is a more symmetrical flow pattern. This suggests there should be differences in a given DP meters wet gas response depending if the meter is installed horizontally or vertically. To investigate this CEESI tested a 4”, schedule 80, 0.6 beta ratio with natural gas / kerosene and then natural gas / water in horizontal and vertical up orientation and compared the results. The results are shown in Figures 24 & 25 respectively.

Figure 24 shows three set natural gas / kerosene flow conditions for horizontal and vertically up flows. All horizontal and vertical up flow conditions were seen with the view port to be annular mist flow. (That is, there was no churn flow tested.) The homogenous model for the two set gas to liquid density ratio values are also shown. At the low gas to liquid density ratio (approximately 0.013) and moderate gas densiometric Froude number (approximately 2.4) combination the horizontal data set has an over-reading well below the homogenous model. However, the vertical up flow, which is inherently more symmetrical than the same flow conditions in horizontal flow is very close to the homogenous model (for the DR 0.013 case). For the moderate gas to liquid density ratio (approximately 0.045) and moderate gas densiometric Froude number (approximately 2.4) combination case the horizontal and vertical up flows have over-readings much closer to each other. In fact they straddle the DR 0.045 homogenous flow model over-reading prediction with the horizontal flow being slightly below the vertical up flow data. This suggests that the flow patterns between horizontal and vertical are very similar and close to the homogenous model. The fact that the vertical up flow has an over-reading slightly greater than the homogenous model simply indicates that the meter can interfere with a homogenous inlet vertical up flow as well as when the flow is horizontal. The highest gas dynamic pressure flow had a moderate gas to liquid density ratio (approximately 0.045) and high gas densiometric Froude number (approximately 4.7) combination. Here, the horizontal and vertical flows gave almost identical over-readings and these were very close to the homogenous model strongly suggesting that this is the flow meters homogenous flow condition.

Figure 25 shows three set natural gas / water flow conditions for horizontal and vertically up flows. Again all horizontal and vertical up flow conditions were seen with the view port to be annular mist flow. Inspection of Figures 25 and 26 shows that exactly the same trends exist for both the gas / kerosene and gas / water flow cases. That is at low gas dynamic pressure the horizontal flow can have an over-reading well below the homogenous model while the same flow condition vertical up has an over-reading very close to the homogenous model. At higher gas dynamic pressures all the flows tested converged on the homogenous flow condition.

A consequence of the fact that the vertical up flow tends to be more symmetrical and hence tends to homogenous flow at lower gas to liquid density ratio and gas densiometric Froude numbers is that for wet gas flow correlation creation there is an advantage to using vertical up installations. The system is less sensitive to liquid property and gas densiometric Froude number effects (after some relatively low critical value is exceeded). Vertical up wet gas correlations are therefore potentially easier to fit as less parameters have to be accounted for. However, it is clear from Figures 24 and 25 that existing DP meter wet gas flow correlations based on data from horizontally installed meters are not particularly applicable to vertical up wet gas flows as significant differences can be found between the same meters response to the different orientation.

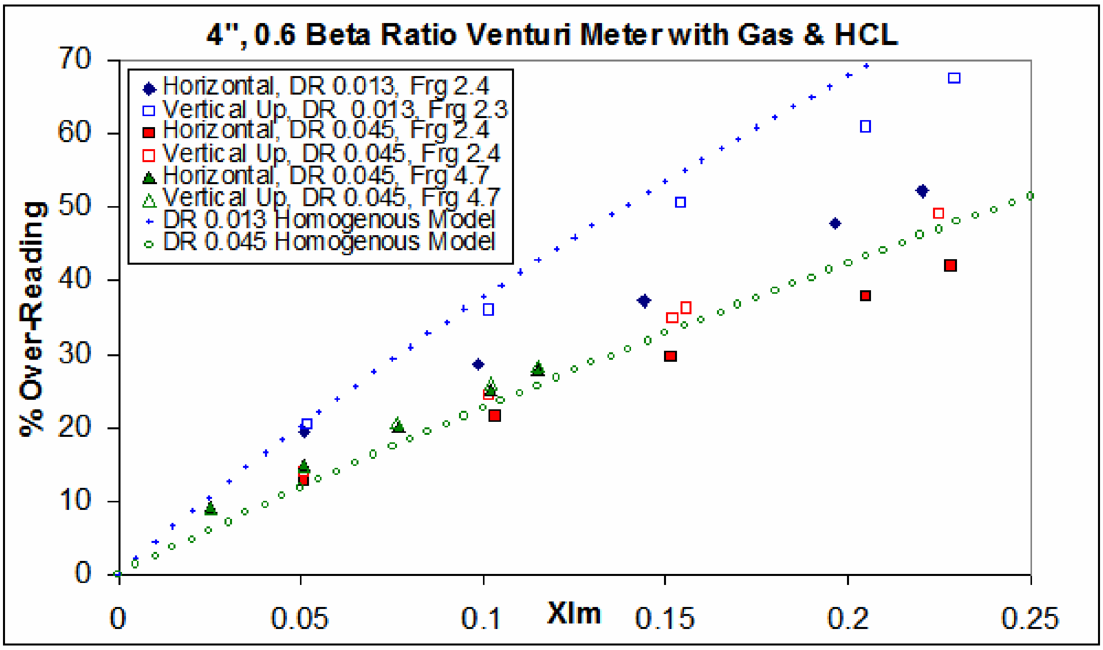

Fig 24. 4", 0.6 Beta Ratio Venturi Meter, Natural Gas & Kerosene Horizontal & Vertical Up Data.

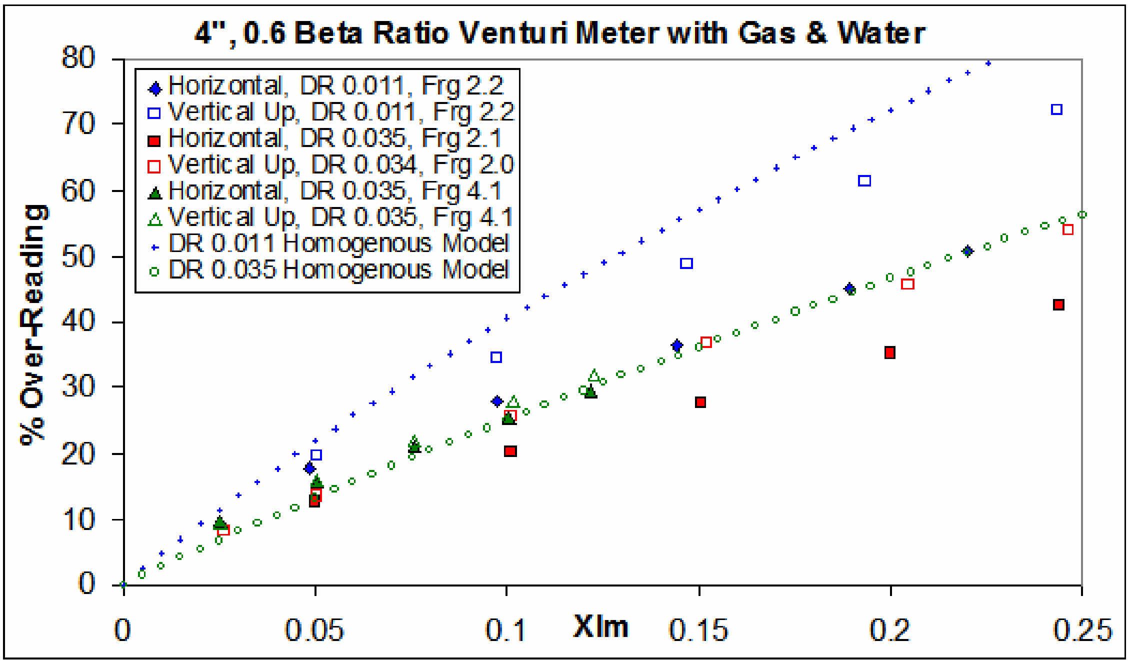

Fig 25. 4", 0.6 Beta Ratio Venturi Meter, Natural Gas & Water Horizontal & Vertical Up Data.

Finally, it is interesting to note that the same meter design gives significantly different over-readings for the same wet gas flow conditions when it is installed in a different orientation. Technically it should be possible to place two similar DP meters in series, one horizontally installed the other vertically up installed and create a wet gas metering system that uses the measurement by difference technique discussed as design type 3 in the introduction. (Such a wet gas flow meter concept was first suggested to the authors by Hans van Maanen of Shell in 2005.) The limitation of such a system would be the same as with all wet gas systems with two DP meters in series (as described by Steven [10, 21]). As the gas dynamic pressure increases tending the wet gas flow to a homogenous flow the individual meters experience a flow tending to pseudo-single phase flow and the difference in the over-readings diminishes until at homogenous conditions there is little to no difference to use as a measurement.

7 CONCLUSIONS

Many wet gas flow metering applications use DP meter based technologies. The response of a DP meter to wet gas flow is very complex and there are multiple variables to take into account. Industry has a lot of work to do before the generic DP meter wet gas flow response is fully understood across the wet gas flow ranges the DP meter is currently being applied to.

In this paper it was confirmed that with all other flow conditions held steady through a wet gas flow DP meter, changing the liquid properties causes a change of response. That is, DP meters with wet gas flows are sensitive to liquid property and for cases where the liquid is more than one component (i.e. a WLR exists) it is not always technically correct to assume the liquid is homogenously mixed and the liquid properties can therefore be averaged.

Research into the effect of diameter (meter size) on wet gas flow response gave the unexpected result that between 2" and 4" Venturi meters of the same 0.6 beta ratio, no significant difference could be seen for the majority of the data. This does not preclude the possibility that different diameter steps across different flow condition ranges could in future show some diameter effect on the DP meters wet gas flow response.

The change in orientation of the 4", 0.6 beta ratio Venturi meter between horizontal and vertically up flow was seen to produce significant differences in the meters wet gas flow response. The vertical up flow was always closer to the homogenous model over-reading prediction than the horizontal flow. As the gas to liquid density ratio and / or gas densiometric

Froude numbers increased the difference between the two different orientations diminished and disappeared. This was directly relatable to theory regarding the relationship of DP meter wet gas flow over-readings and flow patterns. This result suggests that existing horizontally based DP meter wet gas correlations should not be applied to vertically up installed DP meters.

Dimensional analysis can produce a set of dimensional groups for multiphase wet gas phase flow through a DP meter to aid researchers fitting wet gas DP meter data. As proof of the concept it can be seen that when the explicit and implicit limiting assumptions of various researchers are allowed for, then the generic set of dimensionless groups correctly showed similarity with the correlation in question.

Whereas, it is not yet confirmed whether a DP meter wet gas flow diameter effect exists it is confirmed that orientation and liquid properties do have an effect. Dimensional analysis can not help with the orientation issue. Each wet gas correlation has to be for a dedicated meter orientation or the correlation must have an orientation term built in by flow modeling. Recent research, including that shown in this paper, confirms that there is a significant liquid property effect but at the time of writing it is not yet known what dimensionless groups would best fit the data.

From a practical stand point, with more factors being found to influence the magnitude of gas DP meter wet gas flow over-readings more factors are required to be accounted for in the corrective equations. However, the more factors there are the greater the uncertainty in the overall correction. For this reason and to avoid unnecessary complexity it is likely that new correlations will not include geometry or orientation terms but rather, new correlations will be based on one geometry of DP meter in one orientation. However, it is not practical to apply this policy to the case of liquid properties. In many wet gas flow applications there is a mix of water (sometimes salt water) and hydrocarbon liquids and this can change in composition through the useful life of a DP meter. It is therefore desirable that this can be accounted for by a set correlation or flow model. Further research is required.

Industry is still far from having a full set of trustworthy two-phase / wet gas DP meter correlations and much testing remains to be conducted to derive the best form of dimensionless groups and to ultimately obtain satisfactory metering solutions to the huge and diverse array of two-phase flow conditions regularly encountered.

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