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North Sea FLOW Measurement Workshop

Paper 7.1

New Correction Method For Wet Gas Flow Metering Based on Two Phase Flow Modelling: Validation on Industrial Air/Oil/Water Tests at Low And High Pressure

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1 INTRODUCTION

Wet gas metering represents a growing interest for upstream oil and gas area where most of gas produced from gas and gas condensate reservoirs is associated with liquid phases coming from the reservoir themselves or from condensation in systems (wells , flow lines ..). Even if there is no liquids (water and hydrocarbon condensates) coming from reservoirs, liquid condensation can occur in flow lines used to transport gas from reservoir to surface installations because of the reduction in pressure and temperature between subsurface reservoir (up to 700 bar or more for high pressure layers) and surface.

From an user point of view and depending on applications wet gas metering solutions shall provide accurate gas flow rates information but also information on liquid quantity & type.
The liquid phase can be oil condensate, water or both.
.
Wet gas metering shall be applicable to subsea gas fields developments but also to mature fields coming to the latest stages of their production lives.

The main benefits of such wet gas metering system are the following:

- Improved reservoir monitoring
- Capability for well behaviour diagnostic
- Real time monitoring
- Accurate well metering and allocation
- Production optimization
- Installation simplification in challenging developments (subsea)
- Upgrade of existing installations

The needs in wet gas metering are increasing mainly due to more constraints in accurate measurements and also to more challenging situations where conventional separation based metering systems are not appropriate.
Besides, some small wet gas fields could not be developed with their own infrastructures and so are being tapped by running their wet gas flow to the neighbouring main well's production pipeline upstream of the separator. There is then a real need to measure the production of these wells before the mixing point and not after the separator, as it is usually done.

2 WET GAS METERING SYSTEMS

Most of wet gas metering systems use differential pressure measuring systems to get a primary flow related information. One of the most suited differential pressure systems is the Venturi meter which are mainly used in three different ways:

- Single Venturi: liquid information is injected in a venturi correlation which then gives the gas flowrate.
- Venturi meter combined with another gas flow meter used in series. The two devices have different behaviour which allow to predict the actual liquid quantity and calculate the gas flow rate.

- Venturi meter in association with phase fraction measurement devices (e.g. microwave systems, dual energy densitometers, optical systems…): the venturi pressure signal readings are interpreted using phase fraction information and wet gas flow model through a venturi, in order to predict the actual gas and liquid flow rates.

All venturi based wet gas meters do require correction factors or more advanced models for pressure drop measurements interpretation. This latter method is the one TOTAL, GDF Suez and ONERA choose to improve the accuracy & the performance of wet gas metering systems.

Our approach consists in understanding the basic physical phenomena occurring in the venturi meter in order to model them and deduce the correction laws which take into account the characteristics of the two-phase flow (gas / liquid) upstream of the flow meter. However, the understanding of the phenomena is difficult to reach in real conditions (usually at least 150 bar and 200°C), and our research method consists in analyzing the influence of various parameters at low pressure conditions, with air and water, in order to define which parameters have a significant influence on the metering accuracy. The model developed from experimental analyses is integrated in a numerical code called WEGMOVE © (WEt Gas MOdelling of a VEnturi meter).
This code which has been already tested in two phase conditions with one liquid component is now being evaluated against low and high pressure two-phase flow test results with two liquid components (oil and water) and its accuracy is compared to those of other correlations.

3 WET GAS CHARACTERIZATION

The “wet gas” term currently defines a gas with a relatively small volume fraction of liquid (of any composition). Gas Volume Fraction (GVF) are generally higher than 95% and in some cases higher than 99% Before presenting the model used to characterise and meter the wet gas flow encountered in the venturi, a clear definition of what we call wet gas is needed.

3.1 Typical Parameters Used In Wet Gas Metering Area

One of the most commonly used parameters to describe the relative quantity of liquid in a <u>two-phase flow</u> is the Lockhart-Martinelli parameter. To avoid any confusion, this term should be precisely defined as it has been given different definitions over the years (Hall et al. [9]). The Lockhart-Martinelli parameter was originally introduced for the interpretation of separated flow in horizontal pipes. It was defined through the following expression:

$$X^2 = \frac{\left(\frac{\Delta P}{\Delta L}\right)_l}{\left(\frac{\Delta P}{\Delta L}\right)_g} \qquad (1)$$

where $\left(\frac{\Delta P}{\Delta L}\right)_l$ and $\left(\frac{\Delta P}{\Delta L}\right)_g$ are the frictional pressure losses per unit length of pipe if the liquid and the gas phases are assumed to flow alone. This parameter has been developed in smooth pipes for low Reynolds numbers: it is not suitable for wet gas flows.
This parameter was adapted to differential pressure devices and obtained:

$$X_{LM} = \frac{\sqrt{\Delta P_l}}{\sqrt{\Delta P_g}} = \frac{m_l}{m_g}\sqrt{\frac{\rho_g}{\rho_l}} = \frac{1-x}{x}\sqrt{\frac{\rho_g}{\rho_l}} = \frac{Fr_l}{Fr_g} \qquad (2)$$

It is independent of the flow topology (contrary to the former Lockhart-Martinelli parameter) and the DP meter technology.

This parameter chosen by de Leeuw, Hall, Steven to plot results has also been used for simplicity by present authors.

3.2 Flow Structures In Wet Gas Metering

In most applications, liquids are transported in films and droplets and flow regimes vary from annular to dispersed types.

3.3 Reservoir & Composition Perspectives

According to the definitions given by G. Falcone *et al* [7], there are two types of wet gas:

- Typical wet gas: the reservoir temperature is greater than the cricondentherm, but the surface/transport conditions are in the two-phase region. The fluid is single-phase gas at the initial reservoir conditions. As the pressure and temperature decrease from reservoir to surface, the dew point is met and liquid starts forming from the gas.
- Gas condensate: the reservoir temperature is lower than the cricondentherm and greater than the critical temperature. The temperature remains equal to the initial reservoir temperature. As the pressure decreases in the pipe, a retrograde condensation phenomenon occurs, where the liquid components go back into the gas phase.

4 VENTURI METER CORRECTIONS

4.1 Principle Of Wet Gas Metering Using A Venturi

Mass flow calculations using pressure drop measurements in a venturi are based on the Bernoulli's equation. Although this equation is very successful with flows of homogeneous fluids (a discharge and compressibility coefficients are introduced in order to simulate real flows), it needs to be corrected when a liquid phase, even in small quantity, is present in a gas phase.

For a venturi meter with a given β ratio (=d/D), ΔP_t being the actual differential pressure measured on the flow meter with a two-phase flow, the total mass flow rate of the mixture is :

$$Q_{mt} = C_D \cdot \varepsilon \cdot \frac{1}{\sqrt{\left(1-\beta^4\right)}} \cdot \frac{\pi \cdot d^2}{4} \cdot \sqrt{2\rho_t \Delta P_t} = \alpha\sqrt{2\rho_t \Delta P_t} \qquad (3)$$

In this expression, ρ_t is the apparent density of the mixture. The discharge and compressibility coefficients C_D and ε are given by standards. If the density is replaced by the gas density, the apparent mass flow rate of gas is:

$$Q_{mgs} = \alpha\sqrt{2\rho_g \Delta P_t} \qquad (4)$$

In fact the actual mass flow rate of gas is:

$$Q_{mg} = \alpha\sqrt{2\rho_g \Delta P_g} \qquad (5)$$

A correction factor is then introduced:

$$\phi_g = \frac{Q_{mgs}}{Q_{mg}} = \sqrt{\frac{\Delta P_t}{\Delta P_g}} \text{ , ie } Q_{mg} = \frac{Q_{mgs}}{\phi_g} \qquad (6)$$

In this description, the α factor is supposed to be constant and its variations due to the liquid phase are taken into account in the Φ_g factor.

Different approaches lead to the determination of this correction factor: we can differentiate statistical models from physical ones.

4.2 Correlation

In 2002, Steven compared the performance of seven correlations developed for the correction factor calculation with a new set of data obtained on the NEL wet gas loop.

- Murdock [18]: based on orifice plate meters for separated two-phase flows, but not restricted to wet gas flows.

$$\phi_g = 1 + 1.26 X_{LM} \tag{7}$$

- The equivalent density correction: this model treats the two-phase flow as a single-phase flow with an equivalent density giving the same mass and momentum fluxes than the actual two phase flow. It uses a slip factor K between the gas and the liquid phase.

$$K = \frac{\overline{U_g}}{U_l} \tag{8}$$

It permits to deduce a ϕ_g factor from the following expression:

$$\phi_g = 1 + C.X_{LM} + X_{LM}^{\ 2} \tag{9}$$

$$C = \frac{1}{K}\sqrt{\frac{\rho_l}{\rho_g}} + K\sqrt{\frac{\rho_g}{\rho_l}} \tag{10}$$

If the liquid flows as very small droplets, *K* equals 1 and one obtains a simplified expression.
As we there is no way to determine the *K* factor, Chisholm [6] evaluated the value of the *C* parameter of the equivalent density correction from wet steam measurements with orifice plates and obtained the following expression:

$$\phi_g^{\ 2} = 1 + 2.66 X_{LM} + X_{LM}^{\ 2} \tag{11}$$

- De Leeuw [12] developed a new expression derived from the analysis of data collected in a full-scale multiphase flow test facility with venturi meters. In these tests, pressure varied from 15 to 90 bar and the GVF from 90 to 96%. He observed that the correlation depends on the gas Froude number Fr_g and he proposed the expression (5) for the multiplier parameter, derived from the Chisholm expression:

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Error! Objects cannot be created from editing field codes. (13)

In this expression :

$$n = 0.41 \text{ for } 0.5 < Fr_g < 1.5$$
$$n = 0.606.(1 - e^{0.746 Fr_g}) \text{ for } Fr_g > 1.5$$

The Froude number is defined from the superficial gas velocity U_g (= Q_g/S_{pipe}), the pipe diameter *D,* the acceleration of gravity *g* and the gas and liquid densities ρ_g and ρ_l.

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The results of this comparison showed clearly that the de Leeuw's correlation was significantly better than the others obtained from tests with orifice plate meters with non wet gas two-phase flows. All studies on the subject let us think that the meter geometry has a direct influence on the correction factor. As de Leeuw's and Steven's data sets were taken from different venturi diameters and diameter ratios, Steven established a new correlation from the NEL data, also based on the Chisholm expression, the gas Froude number Fr_g and the gas to liquid density ratio.

$$\phi_g = \frac{1 + AX_{LM} + BFr_g}{1 + CX_{LM} + DFr_g} \tag{15}$$

A, B, C and D are parameters depending on the ratio between gas and liquid densities.

More recently, Stewart et al. [25] compared the correlations given by de Leeuw and Steven [22]. They showed that the influence of the β ratio must be taken into account explicitly in the analytical expressions.

4.3 Limitation Of Available Correlations

- Wet gas correlations do not take into account the fluid properties (viscosity, density and surface tension), whereas it seems to be of a great influence. Indeed, Reader-Harris *et al*. [20] tested three different gas-liquid duos on wet gas flows with a venturi meter: argon-kerosene, nitrogen-water and nitrogen-kerosene. They compared their data with the De Leeuw correlation. They found that the nature of the gas and liquid tested had respectively a low and significant impact on the efficiency of the correlation. In a same way, Steven [23] collected data performed in similar conditions from different flow loops with different fluids: nitrogen-diesel, natural gas-decane, natural gas-water. The comparison of the de Leeuw's corrections for each case showed that there was no difference between two different gases or two different light liquid hydrocarbons. However, there was an important difference in using water or light liquid hydrocarbon as the liquid phase. Moreover, surface tension is an important parameter in characterizing the droplets formation phenomenon which occurs in pipes. We can then deduce that the correlations used to meter wet gas could show a better performance if they took into account the fluid properties.
- As discussed before through Steven's proposal for a new correlation, the meter geometry is also an influent parameter. Reader-Harris *et al*. tested three venturis with different beta ratios and convergent angles. They noticed that the de Leeuw's correlation losses its efficiency when meter geometries diverge from the geometry used to develop the correlation.
- All the above correlations require the liquid flow rate as an initial input. Consequently, the correlations accuracies are duly affected by the liquid flow rate uncertainty.

Therefore, wet gas meter accuracy means capability to take into account fluid properties, venturi geometry and access to liquid information.

4.4 Advanced Modelling To Correct Venturi Wet Gas Flow Meter : Analytical Approach

Another approach for the liquid and gas mass flow rates calculation consists in developing and implementing models to describe venturi behaviour and interpret measurements.
This is performed writing the equations of the flow occurring in the venturi and introducing closure laws from empirical correlations. A mathematical model is then created, which models the flow occurring in the venturi. It is then important to identify the main phenomena occurring in the venturi and understand the parameters involved in the development of these phenomena.

To simulate the two-phase flow phenomena inside the Venturi, it is necessary to take into account the gas/liquid film interaction near the wall, the gas/droplet interaction in the core

region and also the mass flux of liquid exchanged between the film and the spray (entrainment and deposition of droplets).

An approach initially developed for venturi scrubbers has been followed by Azzopardi ([1], [3][4]) and co-workers (Van Werven *et al.* [26]). They use a one-dimensional approach to describe the momentum exchanges between the gas and the liquid phase along the venturi meter from the inlet of the convergent section to the outlet of the diffuser. The gas friction at the liquid film interface is modelled by the Wallis's correlation [27]. The film thickness is deduced from the momentum balance in the film neglecting the effect of gravity. The transportation of the droplets by the gas is described through a classical equation of motion using a drag force expression for spheres. The liquid mass exchange between the film and the spray is modelled through two mass transfer equations using empirical correlations developed for straight pipes, one for the entrainment rate and one for the deposition rate. Another correlation is also used to take into account extra entrainment phenomena at the convergent/throat junction.

5 DEVELOPMENT OF AN ADVANCED CORRECTION SOFTWARE: WEGMOVE©

ONERA, TOTAL and GDF Suez developed an advanced software, WEGMOVE ©, following this latter approach. This tool permits then both a flow modeling and the calculation of the correction factor ϕ_g.

5.1 Flow Modelling For Delta P Measurement Interpretation

The flow modelling follows the approach used previously by Azzopardi and co-workers (Van Werven *et al.* [26]). Nevertheless, our calculation (Lupeau *et al* [14], [15], [16]) is different because an equation establishes the evolution of the thickness of the liquid film along the venturi. Moreover, the WEGMOVE © code permits the measurement of liquid and gas mass flow rates, directly in situ: all it needs are the geometrical parameters of the venturi meter, the fluid properties, and the ΔP and GVF measurements, which can easily be collected in situ.

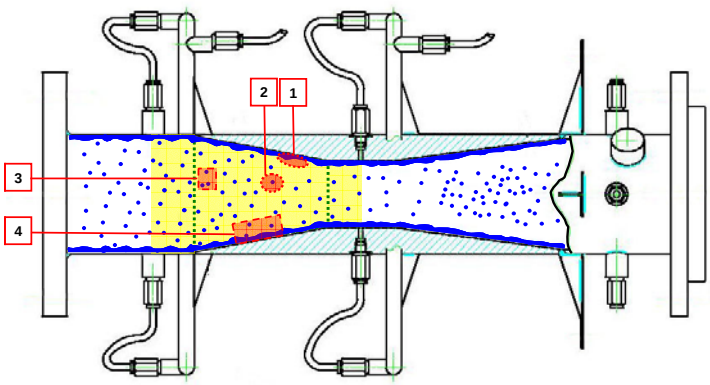

Fig. 1 - Sketch of the gas/liquid interactions in the Venturi meter
1: Gas/liquid film ; 2: Gas/droplets ; 3: Droplet/Droplet ; 4: Droplet/liquid film

The purpose of these studies is to consider the influence of a liquid phase on the global differential pressure (Lupeau [14]). It takes different forms depending on the liquid phase flow regime. Indeed, liquid may flow through the Venturi as droplets or as liquid film. Each form characterises different kinds of interactions with the gas phase.
Then the pressure variation due to momentum exchanges between liquid and gas can be expressed as follow:

$$\Delta P_{WG} = \Delta P_{Bernoulli} + \Delta P_{droplets} + \Delta P_{liquid_film} \tag{16}$$

where $\Delta P_{Bernoulli}$ is induced by the gas acceleration and $\Delta P_{droplets}$ and ΔP_{liquid_film} correspond to pressure drops linked to droplets/gas and liquid film/gas interactions respectively.
So, to accurately model the physical phenomena inside the Venturi, the liquid behaviour has to be analysed properly. From experimental observations a dedicated flow model was developed. In particular a new droplets class appears at the junction between convergent and throat sections of the Venturi due to a partial atomisation of the liquid film. So different phenomena appear in as shown in the following figure:

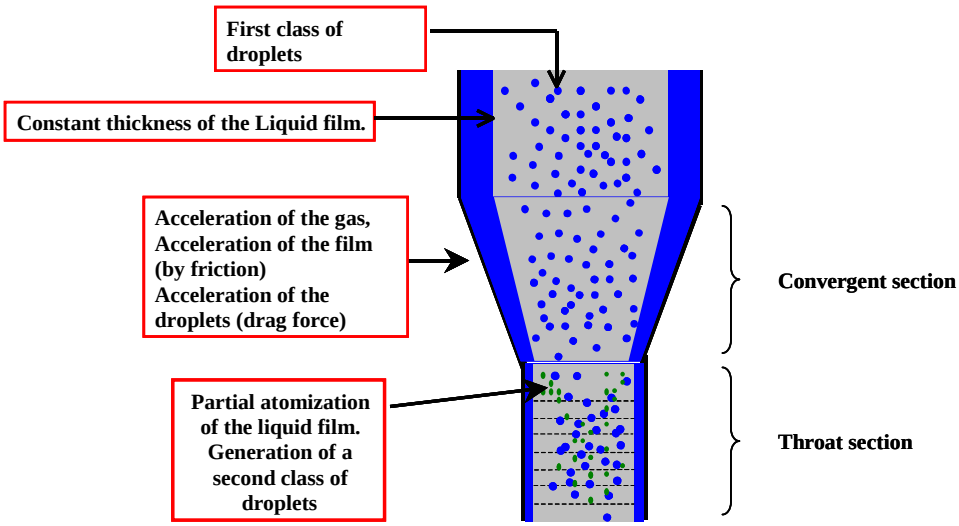

Fig. 2 - The different flow phenomena occurring in the Venturi meter between the two pressure tap

Finally, the following relationship can be written:

$$\Delta P_{WG} = \Delta P_{Bernoulli} + \Delta P_{convergent_droplets} + \Delta P_{atomization_droplets} + \Delta P_{liquid_film} \quad (17)$$

The flow is divided into two regions: the convergent section and the throat. In both zones, integrated balance equations (mass and momentum conservation) are applied to the gas flow, the liquid film and the dispersed flow. Each flow entity is defined by its local velocity v and its flowing area S. In these equations, source terms are used to describe the momentum and mass exchanges. This concerns the momentum gas/liquid film interaction at the interface, the momentum exchange between gas and droplets and the mass exchange between the film and the droplets due to the entrainment. According to the work of Azzopardi and Van Werven *et al.*, this mass exchange has a great influence on ΔP at the end of the convergent section, and can be neglected everywhere else. Actually, at the end of the convergent section, ligaments are detached from the waves formed on the liquid film, and are atomized in droplets. The model supposes that no mass exchange between the liquid and the gas occurs in the meter (evaporation and condensation).

5.2 Wet Gas Flow Prediction In Venturi

This modelling work is well summarized when we plot the evolution of the film thickness and the gas and droplets velocities obtained by the WEGMOVE © code along the venturi meter.

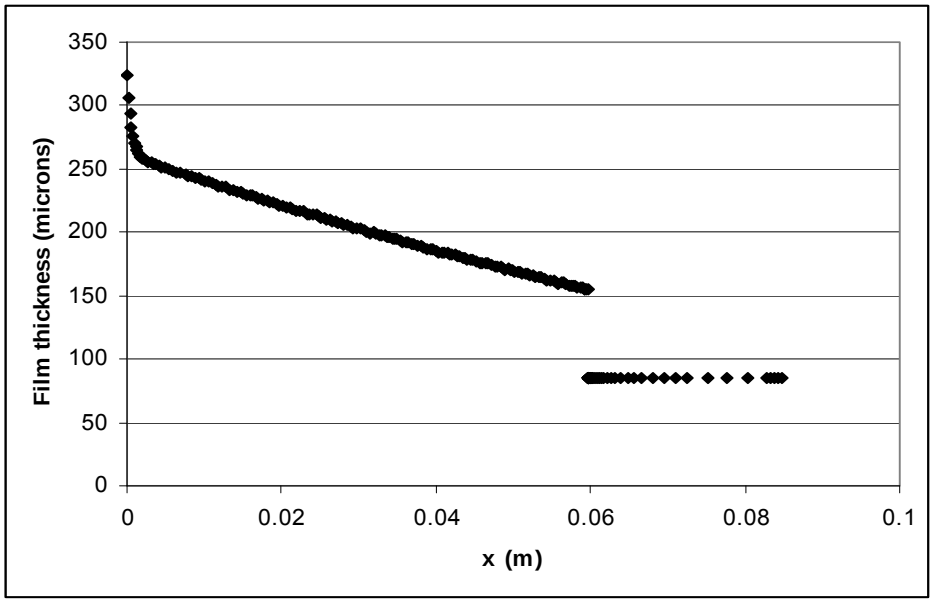

Fig. 3 – Distributionof the film thickness in the venturi meter

We can see in figure 3 the effects of several modelled phenomena on the film thickness. First, a shearing effect: the film thickness reduces with the approach of the throat because it is flattened against the wall by a growing interface constrain linked to the gas velocity acceleration. Another significant phenomenon is the atomization at the throat: we consider that an important atomization phenomenon, linked to the film thickness at the end of the convergent section, occurs suddenly at the convergent/throat junction. The film thickness is then assumed to be constant in the throat. In the case of the figure (which is plotted from real wet gas data), we can notice that the flow type after the venturi meter if of annular dispersed because of the presence of both a liquid film and droplets after the venturi meter.

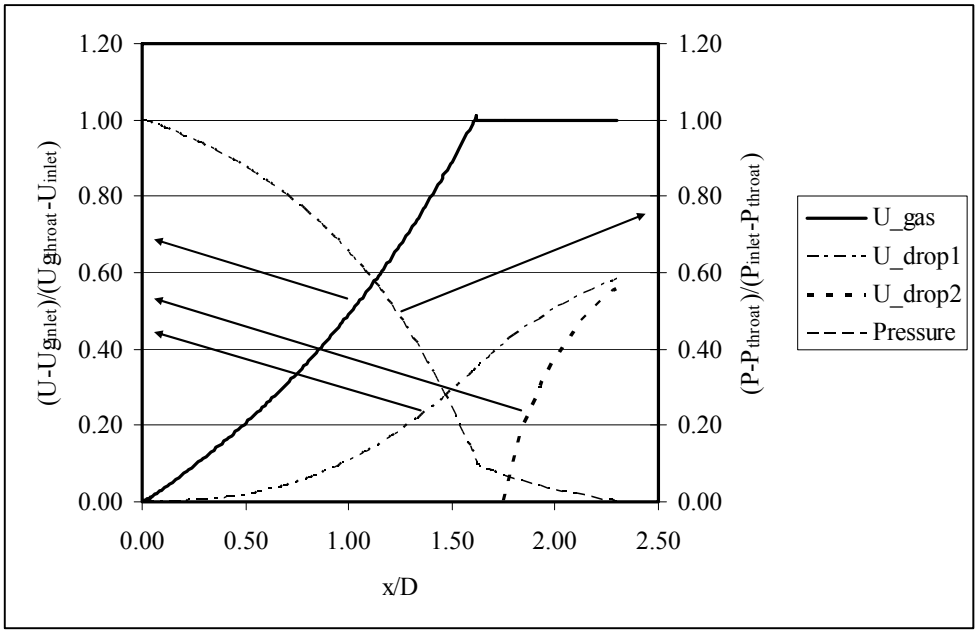

Fig. 4 – Distribution of the gas, entrained droplets and atomised droplets velocities an pressure in the venturi meter

The following aspects of the code can be visualized in figure 4: the gas superficial velocity increases in the convergent section and is constant in the throat section. The gas/droplets interaction induced a concomitant acceleration of the droplets in the convergent section and in the throat. The atomized droplets velocity is non-zero number from the beginning of the

throat and then increases toward the value of the gas velocity. On the pressure curve, we observed that even if the gas velocity is constant in the throat, the pressure continues to decrease due to the droplet acceleration in this pipe venturi part.

5.3 Venturi Flow Rates Calculation Using WEGMOVE Model

In industrial applications the available information are the geometrical characteristics of the venturi meter, the liquid and gas properties, the overall pressure drop ΔP, and the GVF. From these data, WEGMOVE© code calculates the gas and liquid flow rates flowing through the pipe, the distribution of the liquid phase between the film and the droplets, the droplet size and the film thickness. An iterative calculation is used to calculate Φ_g factor.

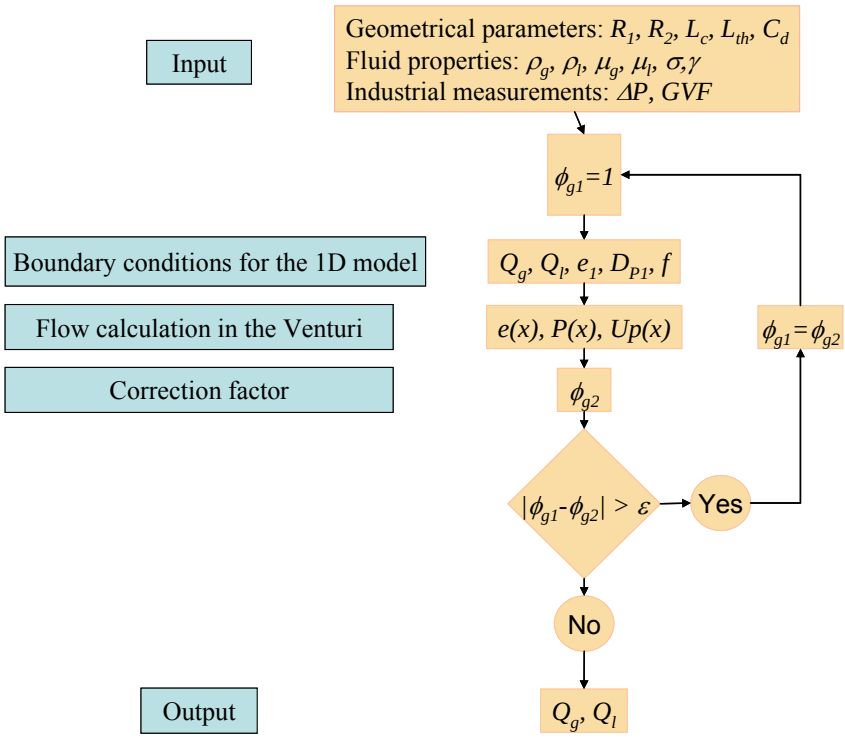

Fig. 5 - Flow chart of the WEGMOVE © code

Boundary conditions determination from industrial inputs:

The boundary conditions for the flow calculation inside the venturi meter are:

- Q_g: inlet gas volume flow rate
- Q_l: inlet liquid volume flow rate
- D_{p1}: inlet droplet size
- f: dispersion factor (ratio of liquid as droplets flow rate on total liquid flow rate)
- e_1: inlet film thickness

We first determine the liquid and gas flow rates, assuming that Φ_g is equal to 1. They are estimated from the ΔP and the GVF. The following expressions are considered:

$$Q_g = \frac{C_D}{\phi_g} \cdot \frac{\varepsilon}{\sqrt{1-\beta^4}} . \pi R_2^{\,2} . \sqrt{\frac{2.\Delta P}{\rho_g}} \tag{18}$$

$$Q_l = \frac{(1-GVF)}{GVF} . Q_g \tag{19}$$

Then, the liquid phase distribution in the pipe is computed from the Ishii [11] correlation which evaluates the dispersion factor f in steady annular/dispersed flow regime.

$$f = \tanh\left(7{,}25.10^{-7}.We^{1{,}25}.\mathrm{Re}_l^{\ 0{,}25}\right) \tag{20}$$

This dispersion factor permits to deduce the liquid film flow rate, and the film thickness.
The size of droplets upstream the venturi, is calculate from the Azzopardi and Govan [4] correlation:

$$D_{p2} = \lambda_T.\left[\frac{15{,}4}{We'^{0{,}58}} + 3{,}5.\frac{Q_{p1}}{Q_g}\right], \text{ with } \lambda_T = \sqrt{\frac{\sigma}{\rho_l.g}} \text{ and } We' = \frac{\rho_l.Q_g^{\ 2}.\lambda_T}{\pi^2.\sigma.R_2^{\ 4}} \tag{21}.$$

After convergence, the code writes in two dedicated files, the overall quantities (mass flowrates, Lockart Martinelli, inlet fil thickness, Stokes numbers, correction factors..) and the distribution in the meter of the film thickness, the droplets velocity and the gas velocity.

The WEGMOVE© code is different from the other approaches in many ways:

- Besides the correction factor calculation, it permits to follow the evolution of all the involved parameters along the venturi meter, in order to predict the flow type or monitor the reservoir behaviour with time.
- As the convergent and the throat lengths and diameters are input parameters of the code, the correction factor is fewer dependants to venturi geometry effects.
- Fluid properties are also input parameters: density, viscosity and surface tension of the gas and liquid phases are then taken into account, what is not the case in the other correlations.
- It is adaptable to horizontal and vertical, upward and downward flows.

6 WEGMOVE MODEL TESTS IN WET GAS CONDITIONS WITH TWO LIQUID COMPONENTS

Three different data have been used to test the WEGMOVE© code performance and to compare it to other wet gas efficient correlations. These data are issued from industrial wet gas two-phase flows with two liquid components (oil and water) at low and high pressure.

Because oil and water are not miscible and have different physical properties, the total liquid behaviour will vary with its composition. Pan [19], observed the flow regimes in gas/water/oil flows. He showed that it is linked to the composition in oil and water of the liquid phase. A useful parameter to describe this composition is the water cut (water to total liquid volume flowrate, as referred to as WC):

$$WC = \frac{Q_w}{Q_o + Q_w} \tag{22}$$

Many configurations exist for the liquid. When oil and water are mixed, it is constituted of a continuous phase (oil or water) in which there are droplets of the other phase (water or oil). To know the liquid configuration of a flow, we need then to know the inversion point value (the WC value which makes the transition between a water-in-oil flow and an oil-in-water flow). WEGMOVE © uses the Odozzi correlation for the determination of the inversion point.

Even if the code has been developed for two-phase flows with only one liquid component, it is possible to use it by considering the water/oil mixing as an homogeneous liquid phase with equivalent physical properties. The following relations are used:

$$\rho_l = \rho_w.WC - \rho_o.(1 - WC) \tag{23}$$

$$\sigma = \begin{cases} \sigma_o & if \quad oil \quad continuous \\ \sigma_w & if \quad water \quad continuous \end{cases} \tag{24}$$

For the determination of the liquid viscosity, Pan developed a correlation introducing a mixing degree coefficient C_m.

$$\mu_l = C_m.\mu_{cont}.(1-\lambda_{dis})^{-2,5} + (1-C_m).\{(1-WC).\mu_o + WC.\mu_w\}$$

μ_{cont} is the viscosity of the continuous liquid phase, and λ_{dis} is the dispersed phase flow rate on the total liquid flow rate ratio. C_m is defined as below:

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where Re_{3P} is a three-phase Reynolds number:

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Here, $\dot{m}$ is the total mass flux per surface unit (kg.m^{-2}.s^{-1}) and U_M is the superficial velocity of the gas/water/oil flow. Its experiments at the Imperial College of London ([19]) permitted Pan to attribute the 15000 value to the κ constant.

6.1 Low Pressure Tests

In 2006, different tests were performed at low pressure. These tests covered wet gas to multiphase flow conditions. Only test results concerning wet gas flow conditions (GVF > 0.95) will be used. The parameters of these tests are presented in Table 1:

Table 1 – Characteristics of the low pressure tests

Upstream pipe diameter D (m)	0.0737		
β ratio	0.7 and 0.71159		
Fluids	Air	Water	Oil
Density (kg/m^3)	4.7 < <12	1000	832
Dynamic viscosity (pa.s)	1.75 10^5<<1.87 10^5	0.00147	0.00611
Surface tension (N/m)	-	0.0747	0.0289
Mass flow rate range (ton/h)	0< < 2.33	0< < 146	0< < 120
P absolute (bar)	6< < 10		
GVF range	> 0.989		
X range	< 0.08		
Water cut range	0< <1		

During these tests, the water cut was varied from 0 to 1. The flow regimes encountered during these tests have been deduced from the Açikgoz three-phase flow map [1]. They vary from annular to annular dispersed.

6.1.1 Tests in two phase flows with only one liquid component (gas/oil or gas/water):

Data treatments focussed on two-phase results with water cut equal to 0 or 1 gives the following conclusions:

- For Air/ Water tests: the correction factors obtained by the WEGMOVE© code are compared to the correction factor calculated from the experimental results or computed from the de Leeuw's correlation. On average, the code underestimates this factor, which induces an overestimation of the gas and liquid mass flow rates. This deviation is equal to 2.5% for low Lockhart Martinelli parameter values and can reach 10% at higher values. In parallel, the de Leeuw's correlation gives better results (E<2%) except for two points for which the deviation reaches 7.5%. Even if these results are not completely satisfactory, we can notice that the code gives the good trends.
- For Air/ Oil tests: we noticed a better behaviour of the code with this fluid. The correction factor is here slightly underestimated but deviations do not exceed 2.5%. It seems that the WEGMOVE© results are on average better than those predicted from the de Leeuw's correlation.

6.1.2 Tests in two phase flows with two liquid components (gas/oil/water):

In figure 6, we use the low pressure test results to visualize the efficiency of the Pan and Odozzi's correlations compared to a model where the inversion point is assumed to occur at WC = 0.5 and the equivalent liquid viscosity is:

$$\mu_l = WC.\mu_w + (1 - WC).\mu_o \tag{27}$$

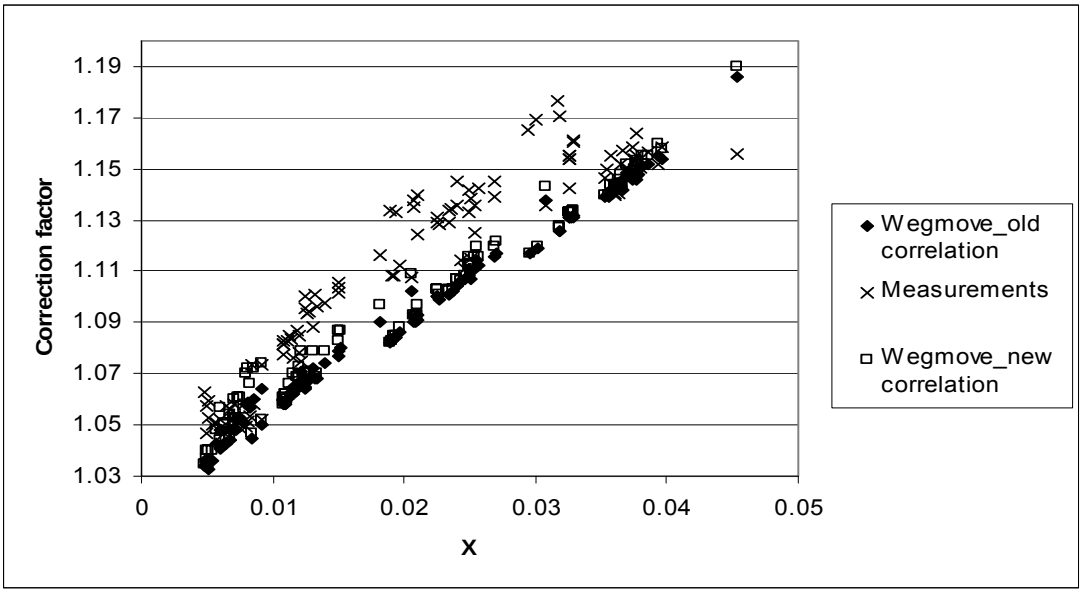

Fig. 6: Comparison old/ new correlation in WEGMOVE

It is clear that the inversion phase phenomena have an influence on the correction factor. The Pan and Odozzi's correlations contribute then to improve the efficiency of the WEGMOVE code. It is specially true for type I wet gas (0<X<0.02).

In figure 7, we compare the results obtained by the WEGMOVE© code (using the Pan and Odozzi's correlations) with two correlations used in wet gas to calculate the correction factor ϕ_g described before.

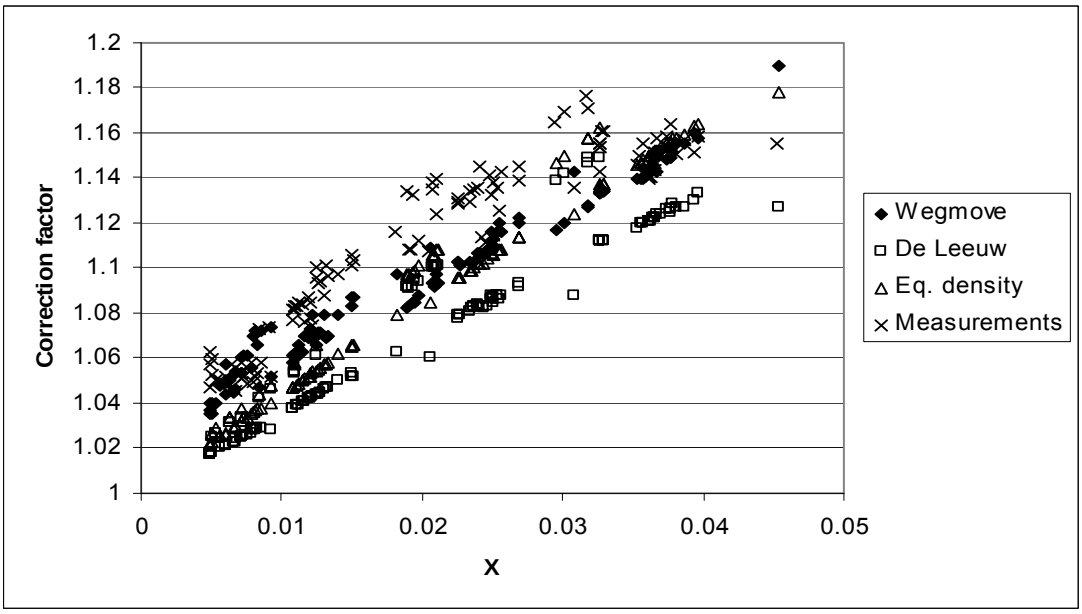

Fig. 7: Comparison of the results obtained by different calculations, for the low pressure tests

On the whole, WEGMOVE© gives better results than the other correlations, especially for type I wet gas (figure 8). Most of the results have accuracy within $\pm 2\%$.

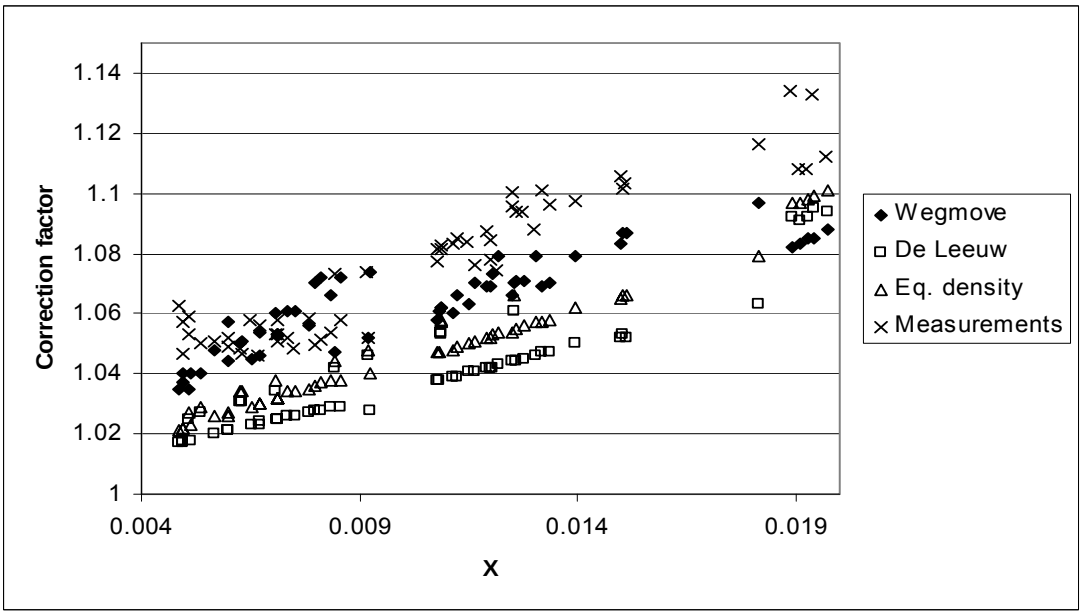

Fig. 8: Comparison of the results obtained by different calculations, for the low pressure tests and type I wet gas

We also remark that the WEGMOVE© error for Air/oil/water flow is not greater that in Air/Water flow on the contrary to de Leeuw's. It seems that this error is globally between the Air/Water and Air/Oil ones.

6.2 High Pressure Tests

Further tests were performed at higher pressure. As before, these tests covered wet gas to multiphase flow conditions but only test results concerning wet gas flow conditions (GVF > 0.95) will be used. The parameters of these tests are presented in Table 2:

Table 2 – Characteristics of the high pressure tests

Upstream pipe diameter D (m)	0.0737		
β ratio	0.7116		
Fluids	Gas	Water	Oil
Density (kg/m^3)	28 < <100	1000	620< <700
Dynamic viscosity (pa.s)	1.59 10^5	4.79 10^{-6}	0.000227
Surface tension (N/m)	-		0.00412
Mass flow rate range (ton/h)	3 < <4.6	< 17.4	< 14
P absolute (bar)	35< < 121		
GVF range	> 0.9		
X range	< 0.25		
Water cut range	0< <1		

The flow regimes encountered during these tests have been deduced from the Açikgoz flow map to correspond to an annular flow regime.

6.2.1 Tests in two phase flow with one liquid component:

Data treatments performed with WEGMOVE© on tests with only oil in the liquid phase are quite satisfactory. It is interesting to notice that the errors obtained with the WEGMOVE© code are always inferior to 2.5%, whatever the Lockhart-Martinelli parameter. The equivalent density correction gives better results for high value of the Lockhart-Martinelli parameter but worse results when this parameter is low. We note also the de Leeuw's correlation is not satisfactory.

6.2.2 Tests in two phase flow with two liquid components:

For high pressure tests, it appears that the equivalent density correction gives better results on the whole Lockhart Martinelli range (figure 9). This is certainly due to the fact that according to WEGMOVE, the liquid flows as droplets in these high pressure tests, so the no slip assumption of the equivalent density correction is valid. The WEGMOVE© code gives equivalent results for Lockhart Martinelli values below 0.1. For higher values, except for three test points, the WEGMOVE© prediction are better than the de Leeuw's.

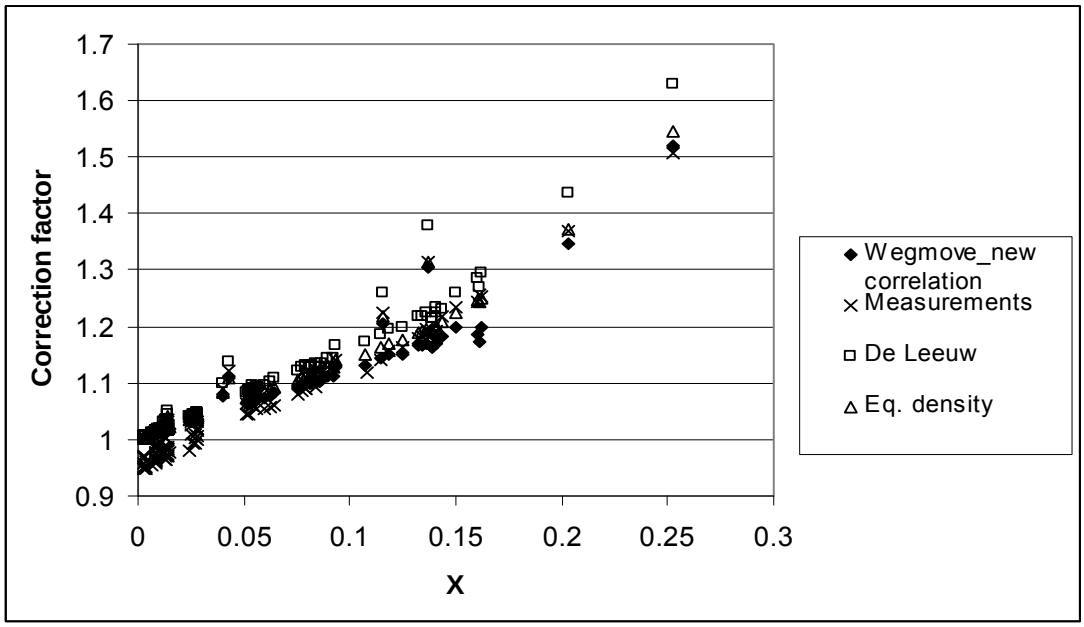

Fig. 9: Comparison of the results obtained by different calculations, for the high pressure tests

7 CONCLUSIONS

The WEGMOVE© code proposes a method to calculate the liquid and gas mass flowrates from the classical outputs of a wet gas venturi meter. This method takes into account the fluid properties, the direction of the flow, the geometry of the metering device. It models some parameters (film thickness, fluid velocities, dispersion factor), which permit to predict the flow evolution along the venturi meter. Besides, the computing time is low (between 5 to 30 secondes per point depending on the flow regime) and the code can be implemented on a classical computer: WEGMOVE© is then easily usable for post-treatment on site.

The WEGMOVE© code is a valid tool for the calculation of the correction factor. On the low pressure with air/water/oil, it shows better agreement than the de Leeuw's correlation and the equivalent density correction. At high pressure, it has a better accuracy than de Leeuw's correlation, which is less satisfactory than the equivalent density correction. However, this point can be ameliorated by the treatment of the dispersed flow in WEGMOVE©.

In order to improve the WEGMOVE© accuracy, further tests are in progress on the ONERA loop at 5 bar, using air/water/oil flow components in order to analyse the real effect of the water cut on the flow regime and on the ΔP measurement, especially around the inversion area.

ACKNOWLEDGEMENTS

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NOTATIONS

C_D	Discharge coefficient	R_2	Throat pipe radius
C_d	Drag coefficient of the droplets	R_x	Local pipe radius
D_{p1}	Diameter of the droplet coming from the upstream of the Venturi meter	U	Actual velocity
D_{p2}	Diameter of the droplet coming from the liquid film atomization at the convergent/throat junction	U_g	Gas velocity
e	Film thickness	Re_g	Reynolds number of the gas phase
g	Gravity acceleration	Re_l	Reynolds number of the liquid phase
GVF	Gas volume fraction	Re_p	Reynolds number of the droplets
P	Pressure	We	Weber number
Q_g	Volume flow rate of the gas phase	X	Lockhart Martinelli parameter
Q_f	Volume flow rate of the liquid film	ΔP	Differential pressure
Q_{p1}	Volume flow rate of the droplets coming from the upstream of the Venturi meter	ΔP_t	Actual differential pressure measured on the flow meter
Q_{p2}	Volume flow rate of the droplets coming from the liquid film atomization at the convergent/throat junction	ΔE_f	Mass fraction of the liquid film atomized at the convergent/throat junction
U_{p1}	Velocity of the droplets coming from the upstream of the Venturi meter	ε	Adiabatic gas expansion factor
U_{p2}	Velocity of the droplets coming from the liquid film atomization at the convergent/throat junction	γ	Isentropic coefficient of the gas
R_1	Upstream pipe radius	μ_g	Dynamic viscosity of the gas
		μ_l	Dynamic viscosity of the liquid
		φ_g	Correction factor
		ρ	Density
		σ	Surface tension
		τ_l	Gas/liquid film interface shear stress

REFERENCES

[1] M. ACIKGOZ, R&T LAHEY Jr, F. FRANCA. An experimental study of three-phase flow regimes, Int. J. Multiphase Flow. 1992. v.18, n.3, p.327.

[2] B.J. AZZOPARDI, S. TAYLOR, D.B. GIBBONS. Annular two-phase flow in large diameter pipes. In: Int. conf. on physical modelling of multi-phase flow. 1983. p. 267-82.

[3] B.J. AZZOPARDI. Drops in annular two-phase flow. Int. J Multiph Flow 1997;23(7):1-53.

[4] B.J. AZZOPARDI, A.H. GOVAN. The modelling of venturi scrubbers. Filtr Sep 1984;21(3):196-200.

[5] J. CAZIN, J.P. COUPUT, C. DUDEZERT, J. ESCANDE, P. GAJAN, A. LUPEAU, A. STRZELECKI. Lessons from wet gas flow metering systems using differential measurements devices : Testing and flow modelling results. International North Sea flow measurement workshop. 2005.

[6] D. CHISHOLM. Two-phase flow through sharp edged orifices. J Mech Eng Sci 1977;19(3):128-30.

[7] G. FALCONE, C. ALIMONTI. Critical review of wet gas definitions. 24th North Sea flow measurement workshop. 2006.

[8] P. GAJAN, A. STRZELECKI, MPM Report. 2006. 2/11646/ ONERA DMAE.

[9] A. HALL, D. GRIFFIN, R.N. STEVEN. A discussion on wet gas flow paramet definitions. 24th North Sea flow measurement workshop. 2006.

[10] J.H. HOLMES. PhD thesis. University of Liverpool. 1970.

[11] I. ISHII, I. KATAOKA, A. NAKAYAMA. Entrainment and deposition rates of droplets in annular two-phase flow. International Journal of Heat and Mass Transfer. 43, p. 1573-1589. 1999.

[12] H. DE LEEUW. Wet gas flow measurement by means of a venturi and a tracer technique. In: North Sea flow measurement workshop. 1994.

[13] H. DE LEEUW. Venturi meter performances in wet gas flow. In: B.H.R. group multiphase'97. 1997.

[14] A. LUPEAU. Etude et modélisation du comportement d'un écoulement annulaire dispersé. Application à la mesure de débit de gaz humide à l'aide d'un débitmètre venturi. PhD thesis. Toulouse, Supaéro. 2005.

[15] A. LUPEAU, J. ESCANDE, J.P. COUPUT, P. GAJAN, A. STRZELECKI. Influence of the characteristics of an annular dispersed flow on the behaviour of a venturi meter. In: 4th North America conference on multiphase technology. 2004.

[16] A. LUPEAU, B. PLATET, P. GAJAN, A. STRZELECKI, J. ESCANDE, J.P. COUPUT. Influence of the presence of an upstreamm annular liquid film on the wet gas flow measured by a venturi in a downward vertical configuration. In: Flow Measurement and Instrumentation. 2006;1-11.

[17] P. MEHDIZADEH, J. WILLIAMSON. Principles of multiphase measurements. Guidelines for qualification of multiphase metering systems for well testing. 2004.

[18] J.W. MURDOCK.. Two-phase flow measurements with orifices. J Basic Eng, Trans ASME 1962;84(4):419-33.

[19] L. PAN. PhD thesis. High-pressure three-phase (gas/liquid/liquid) flow. Imperial College of London. 1996.

[20] M. READER-HARRIS, D. HODGES, J. GIBSON. Venturi-tube performance in wet gas using different test fluids. 24th North Sea flow measurement workshop. 2006.

[21] R.N. STEVEN. Wet gas metering. PhD thesis. Glasgow, University of Strathclyde, 2001.

[22] R.N. STEVEN. Wet gas metering with a horizontally mounted Venturi meter. In: Flow Measurement and Instrumentation. 2002;361-372.

[23] R.N. STEVEN. A discussion on horizontally installed differential pressure meter wet gas flow performances. 24th North Sea flow measurement workshop. 2006.

[24] R.N. STEVEN. A dimensionnal analysis of two phase flow through a horizontally installed venturi meter. Flow Measurement and Instrumentation. 2008.

[25] D.G. STEWART, D. HODGES, G. BROWN. Venturi meters in wet gas flow. In: North Sea flow measurement workshop. 2003.

[26] M. VAN WERVEN, H.R.E. VAN MAANEN, G. OOMS, B.J. AZZOPARDI. Modelling wet gas annular/dispersed flow through a venturi. AIChE J 2003;49(6):1383-91.

[27] G.B. WALLIS. Annular two-phase flow, part 1: a simple theory. J Basic Eng. 92, 59. 1970.

North Sea FLOW Measurement Workshop

Paper 7.2

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

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nel technology for life

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:

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

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

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):

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

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

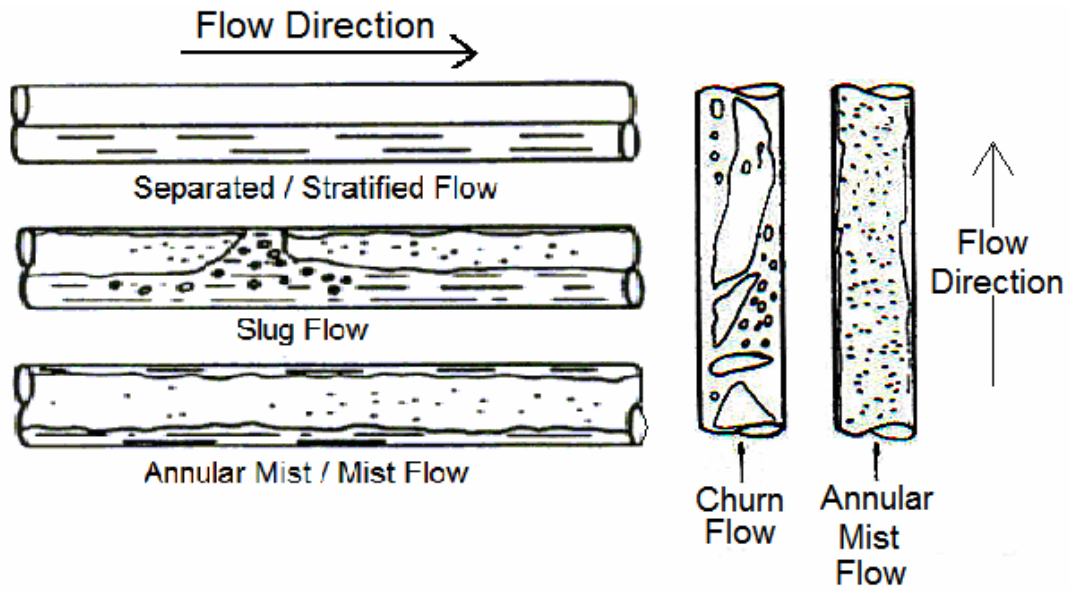

Fig 1. Typical Wet Gas Horizontal and Vertical Up Flow Patterns.

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.

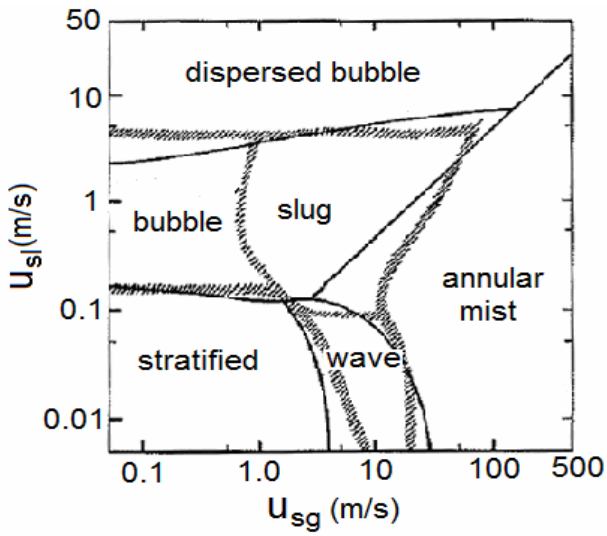

Fig 2. Taitel and Dukler Published Comparison of the Mandhane Map (thick lines) and Taitel & Dukler Horizontal Flow Theory for Air and Water in a 2.5 cm Pipe at Atmospheric Conditions (thin lines).

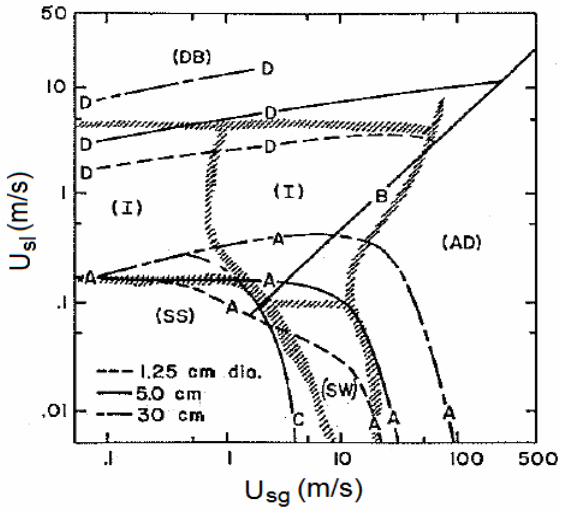

Figure 3a. Taitel and Dukler Published Graph Showing the Taitel and Dukler Horizontal Flow Theory Prediction for Different Pipe Diameters for Air and Water in a 2.5 cm Pipe at Atmospheric Conditions.

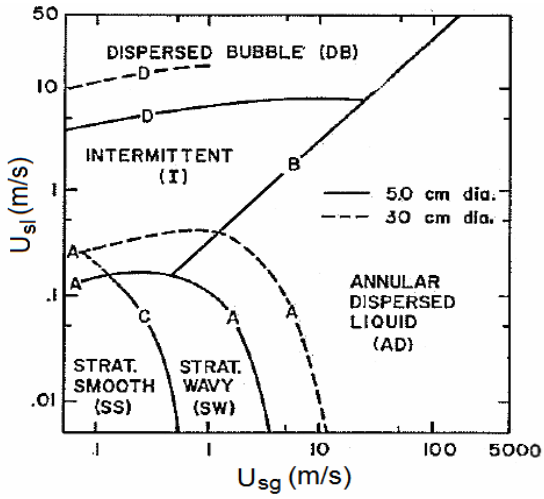

Figure 3b. Taitel and Dukler Published Graph Showing the Taitel and Dukler Horizontal Flow Theory Prediction for Natural Gas and Crude Oil at 30° C and 68 Atmospheres.

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° 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:

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

Flow Condition Terms Geometric Terms

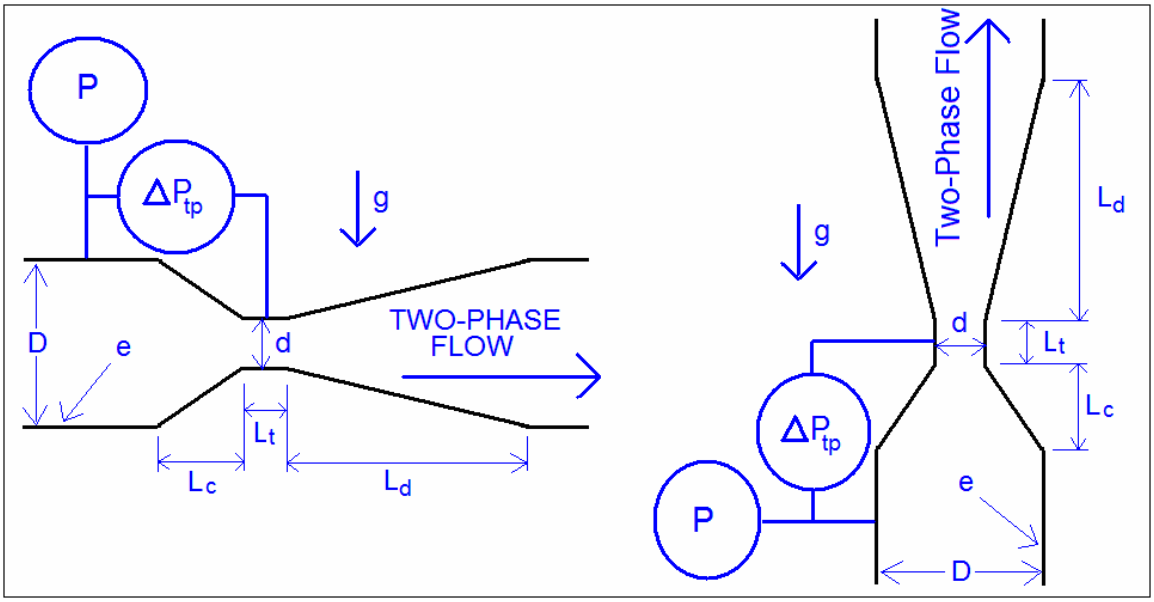

Figure 4. Sketches of Generic Venturi Meters with Horizontal and Vertical Up Flow.

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

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:

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

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. $\dot{m}_g = \dfrac{\dot{m}_{g_{Apparent}}}{\sqrt{1 + CX_{LM} + X_{LM}^2}}$ -- (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.

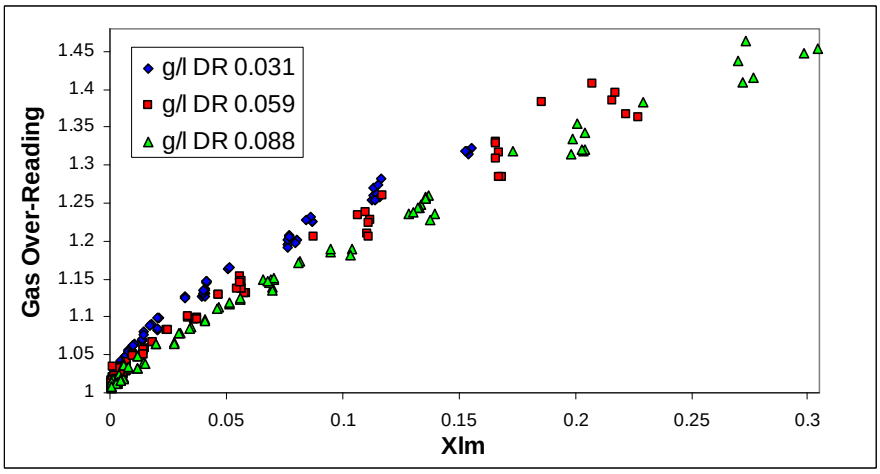

Fig 5. 6", 0.55 Beta Ratio Venturi Meter Wet Gas Data.

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

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

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

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

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.

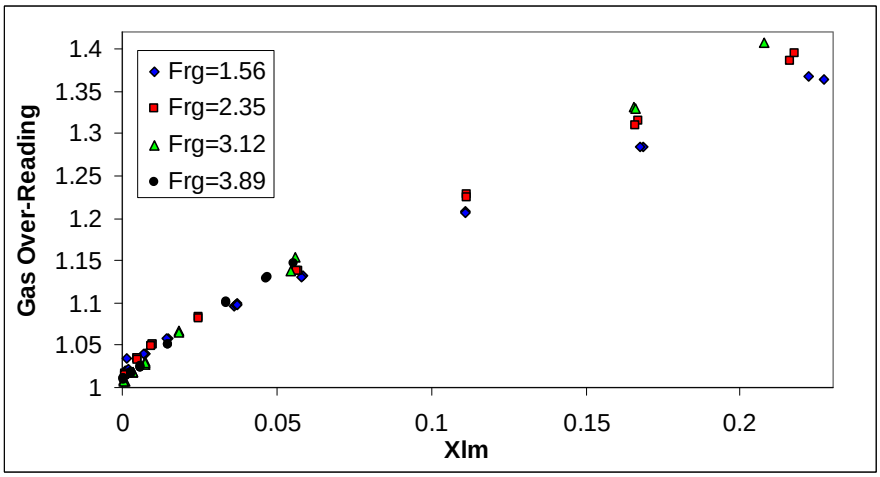

Fig 6. 6" 0.55 Beta Ratio Venturi Meter Wet Gas Data for 41 Bara / DR 0.059.

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.

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

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.

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

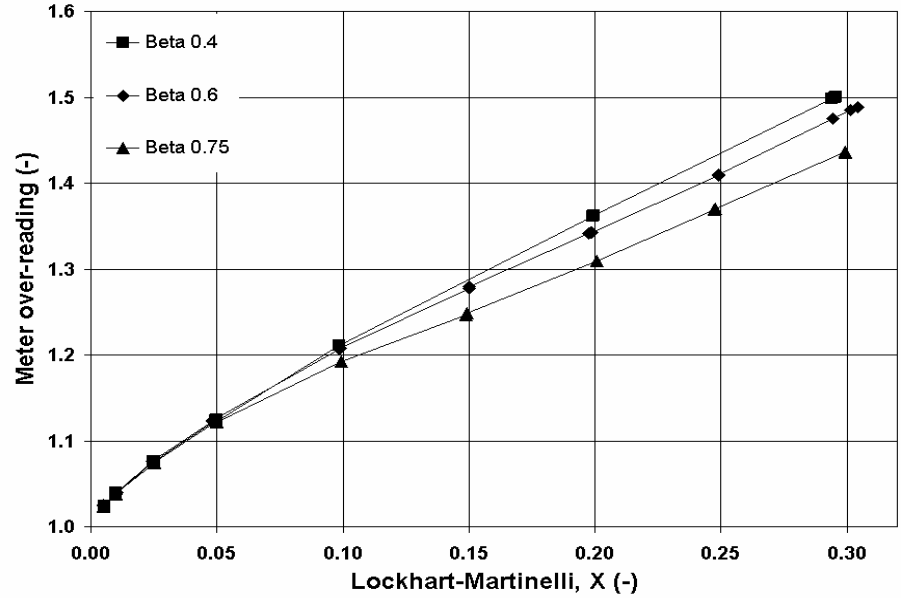

Fig 7. NEL 4", Venturi Meter Wet Gas Data for Nitrogen and Kerosene31 Bar(a), Fr_g=1.5

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.

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

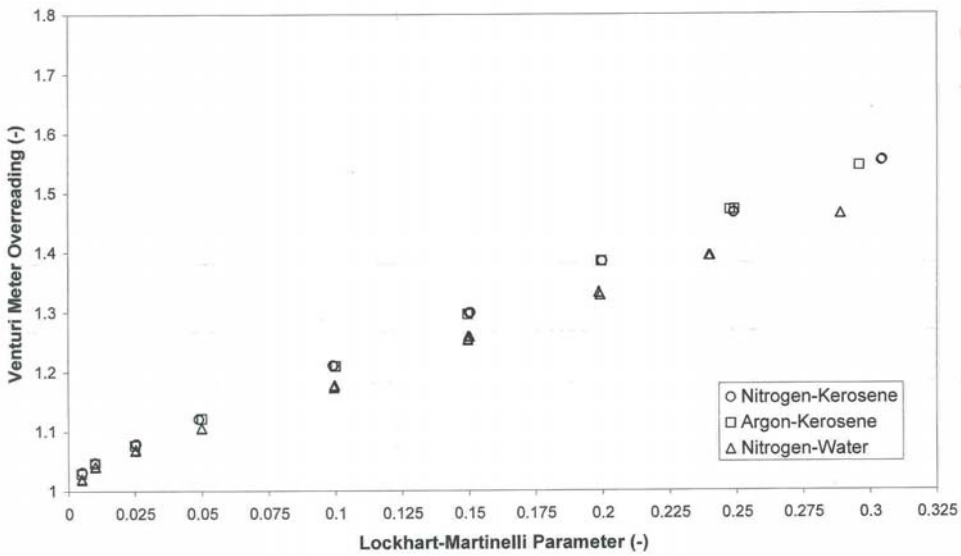

Fig 8. 4", 0.75 Beta Ratio Venturi Meter, DR 0.046, Gas Densiometric Froude Number of 2.5.

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

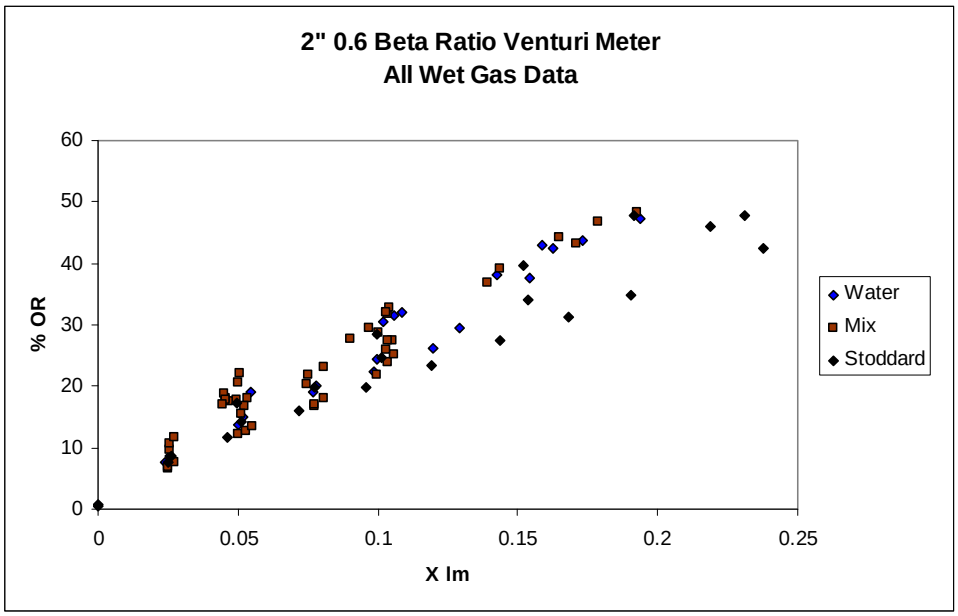

Fig 9. CEESI 2" 0.6 Beta Ratio Venturi Meter Wet Gas Flow Data with Various Liquid Components.

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.

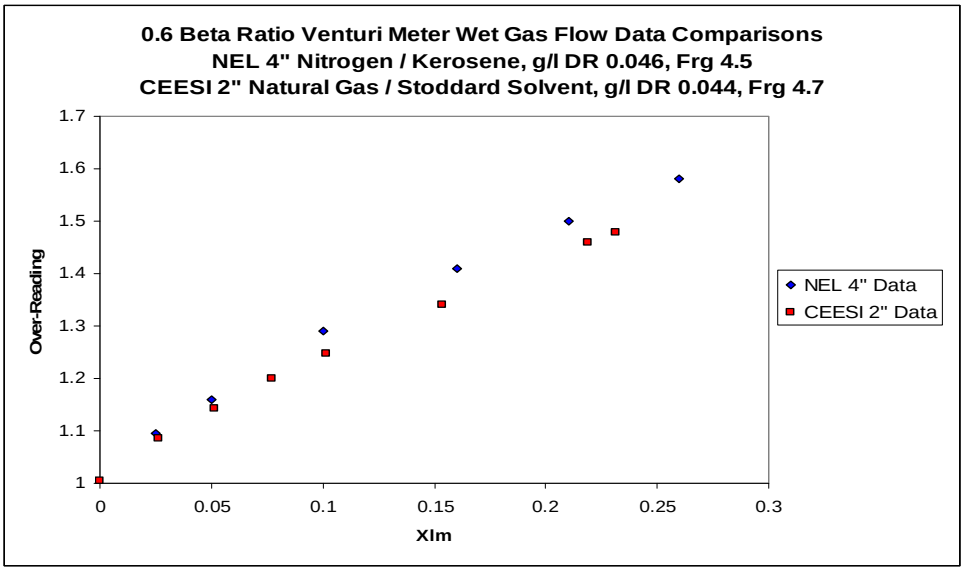

Fig 10. CEESI 2' / NEL 4", 0.6 Beta Ratio, Venturi Meter Wet Gas Response

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.

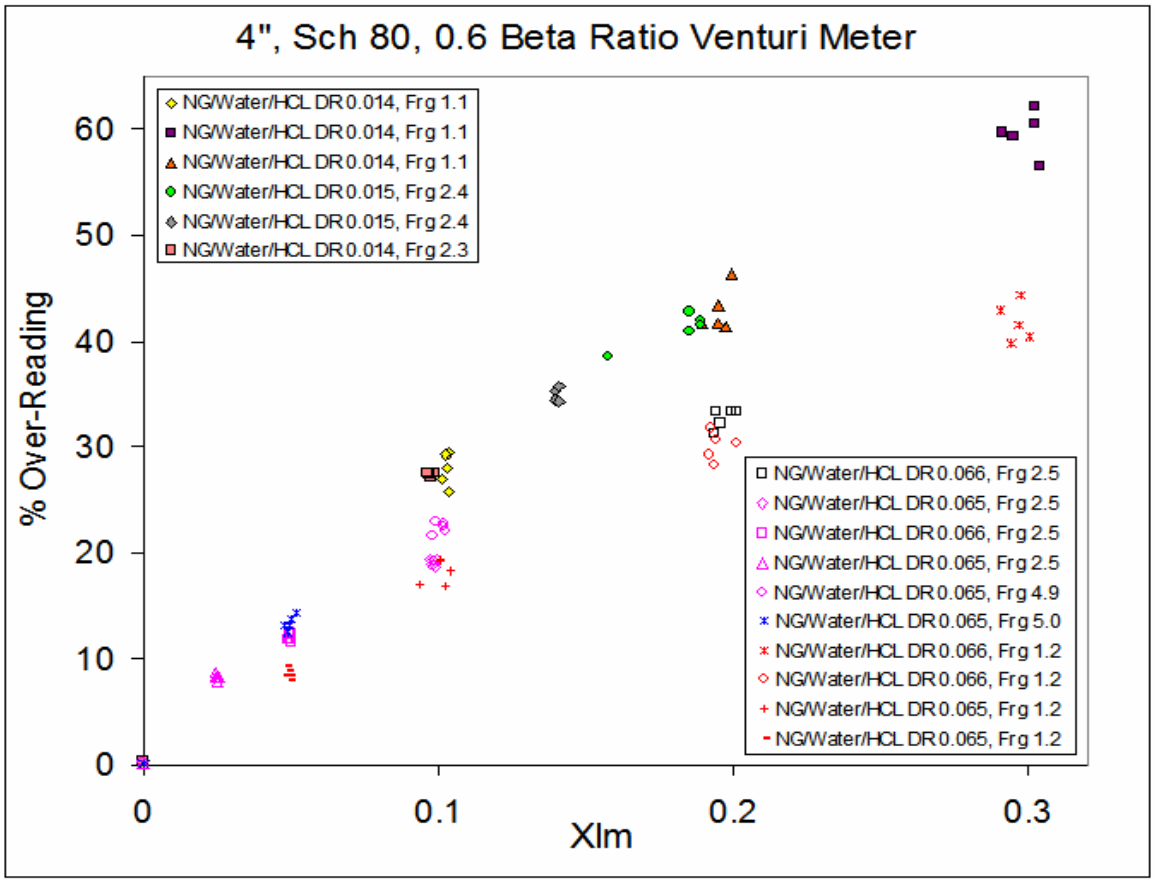

Fig. 11. CEESI Multiphase Wet Gas Flow Test Facility Horizontally 4", 0.6 Beta Venturi Data.

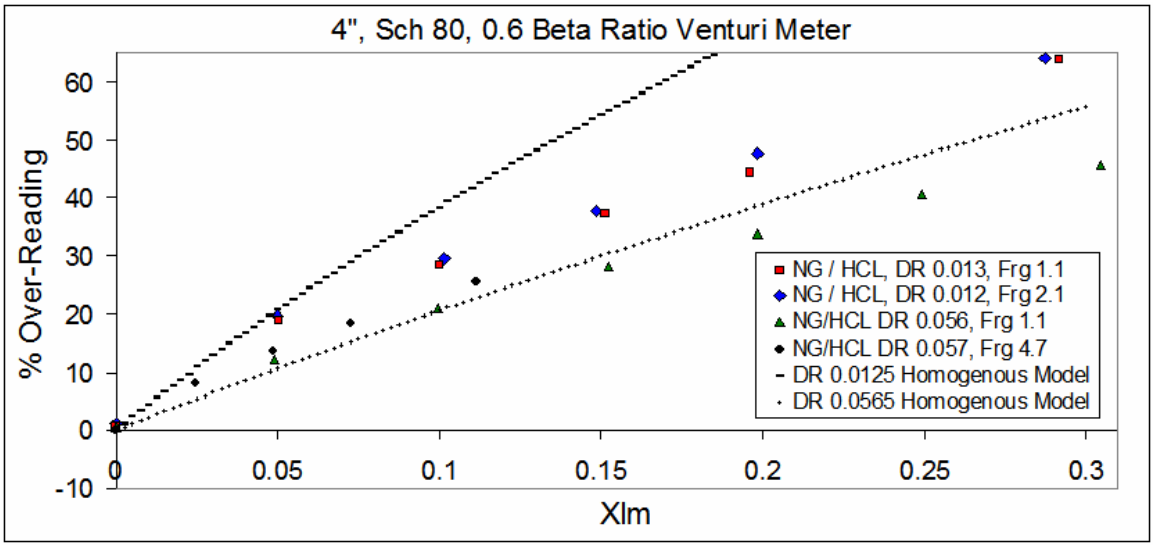

Fig 12. CEESI 4", 0.6 Beta Ratio Venturi Meter Natural Gas / Kerosene Data.

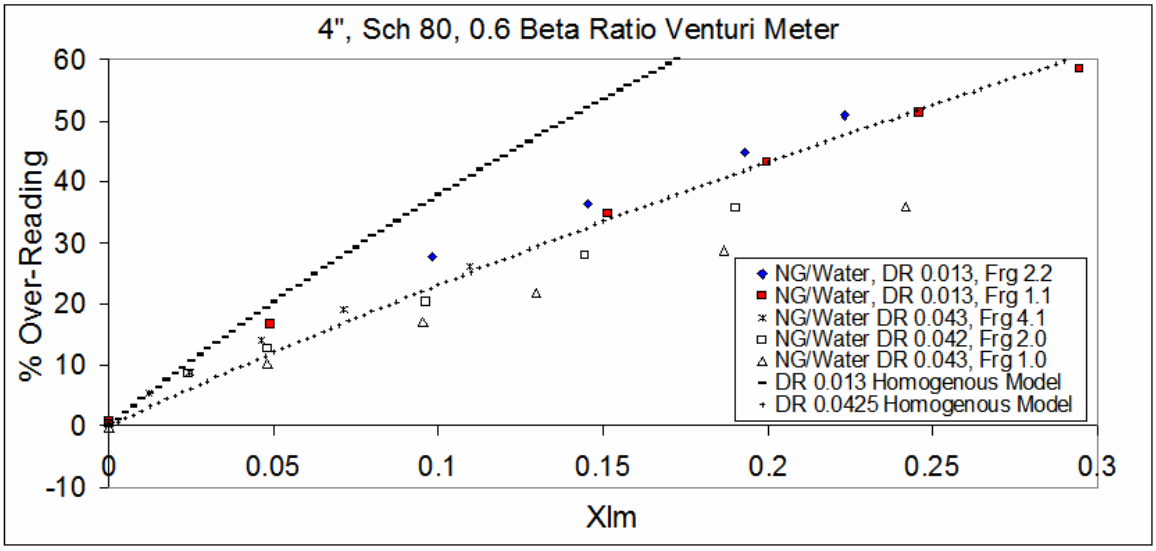

Fig 13. CEESI 4", 0.6 Beta Ratio Venturi Meter Natural Gas / Water Data.

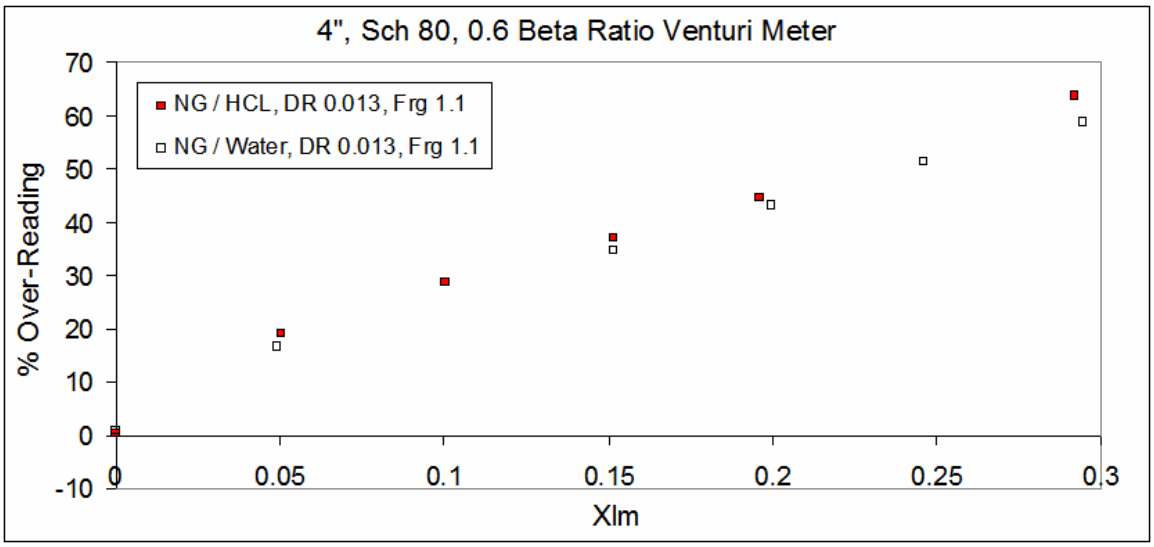

Fig 14. CEESI Low Pressure, Low Gas Flow Rate Data Comparing Kerosene to Water.

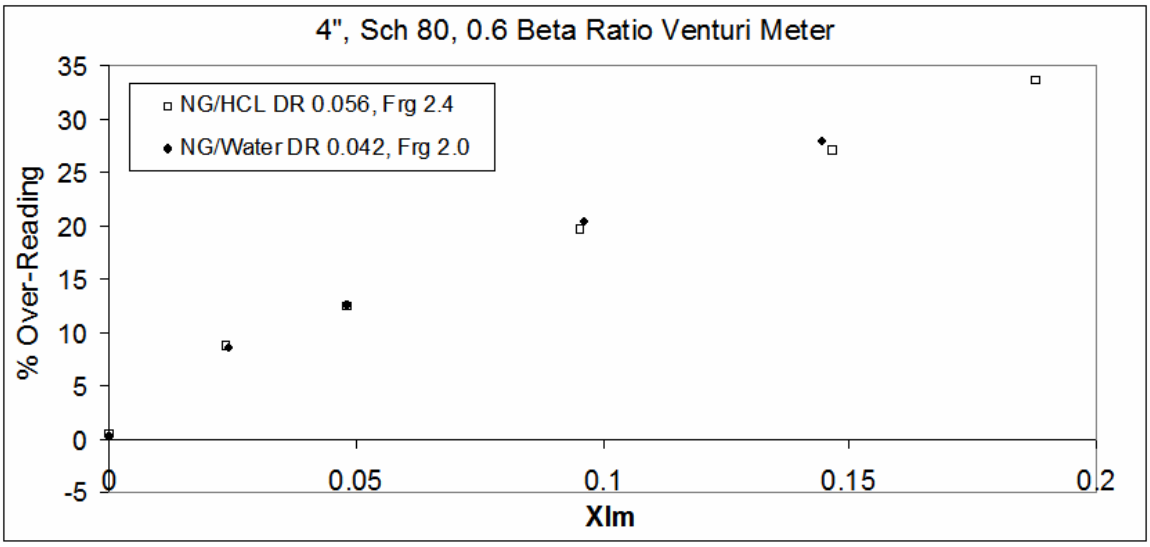

Fig 15. CEESI Moderate Pressure, Moderate Gas Flow Rate Data Comparing Kerosene to Water.

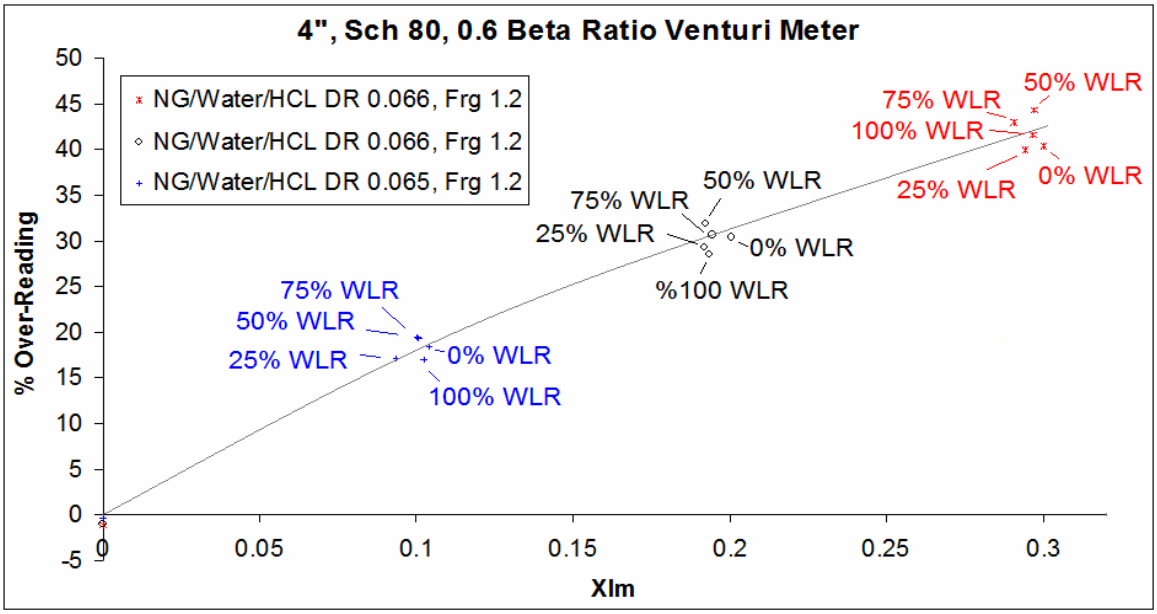

Fig 16. Sample CEESI Natural Gas / Water / Kerosene Mixture Data with Sketched Approximate OR Line.

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

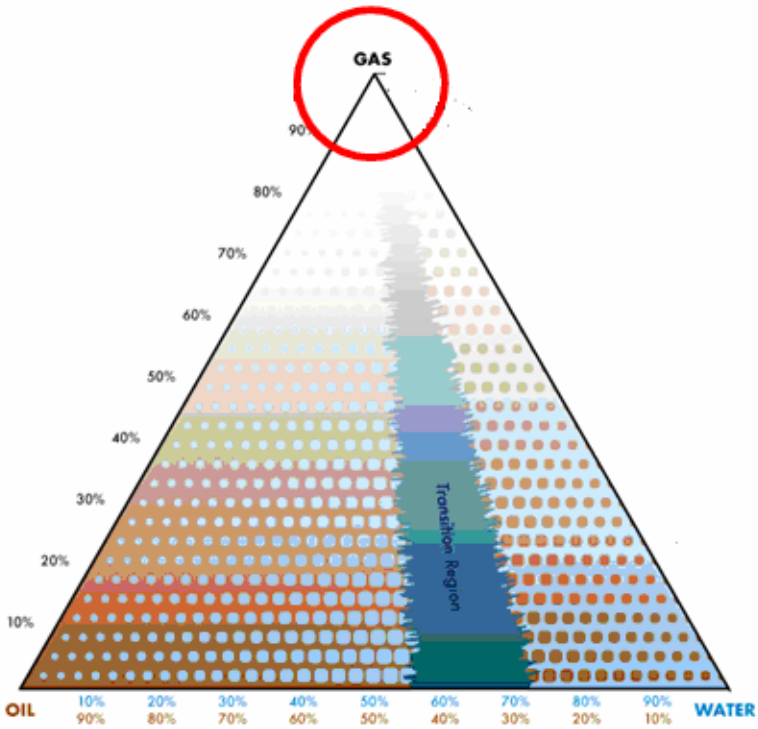

Fig 17. Jamieson's Multiphase Flow Triangle [20].

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:

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

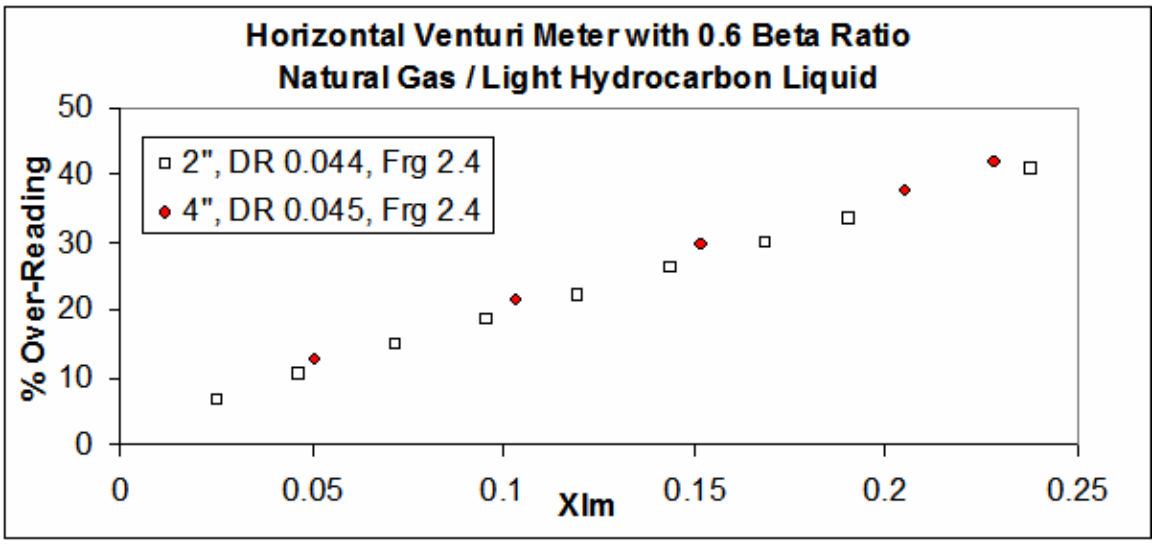

Fig 18. Diameter Comparisons for Gas / Kerosene Moderate Pressure, Moderate Gas Flow Rate Data.

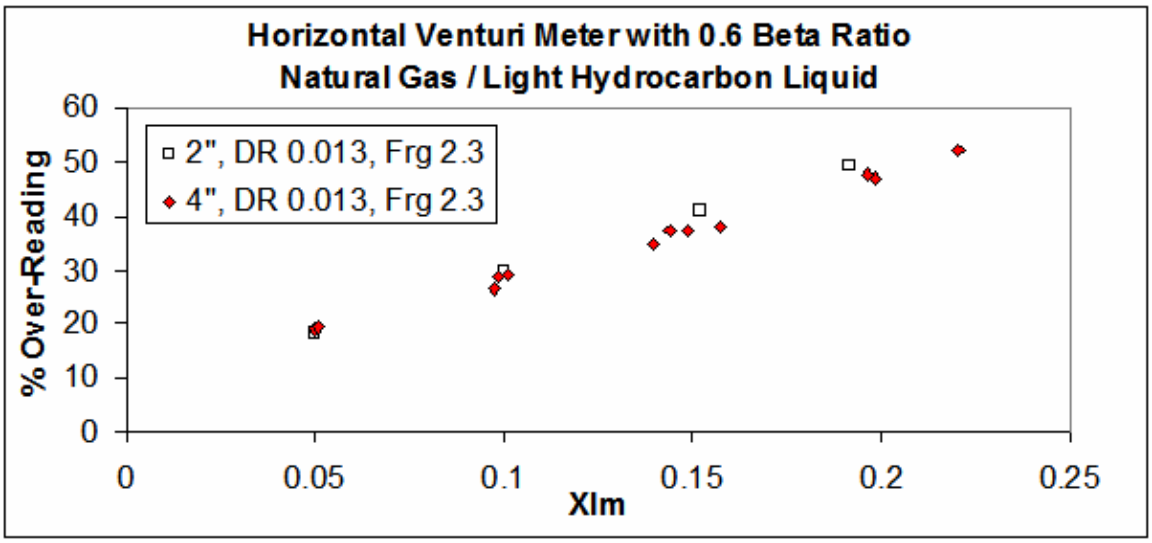

Fig 19. Diameter Comparisons for Gas / Kerosene Low Pressure, Moderate Gas Flow Rate Data.

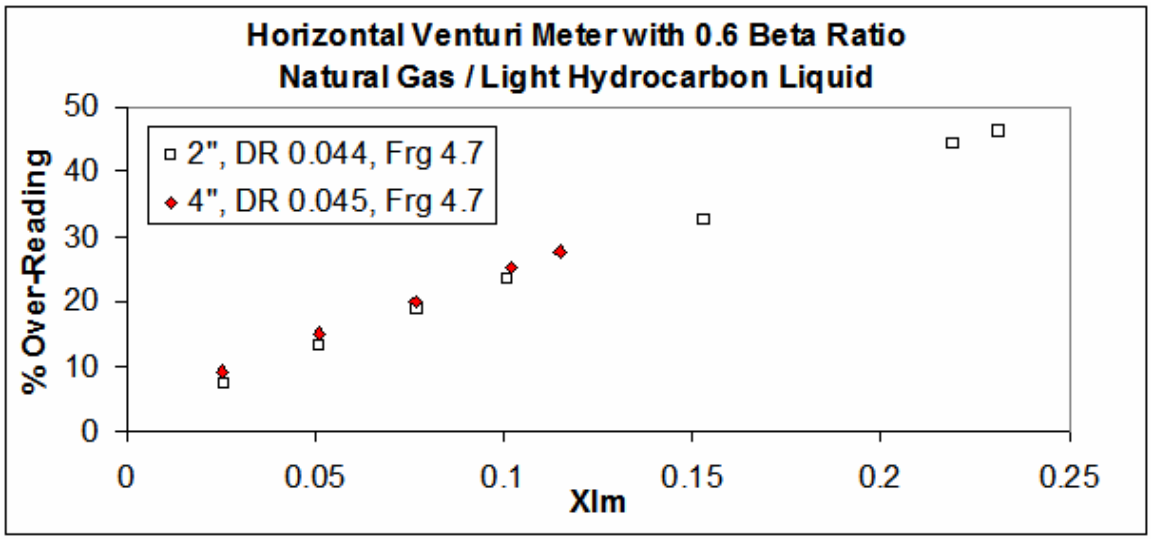

Fig 20. Diameter Comparisons for Gas / Kerosene Moderate Pressure, High Gas Flow Rate Data.

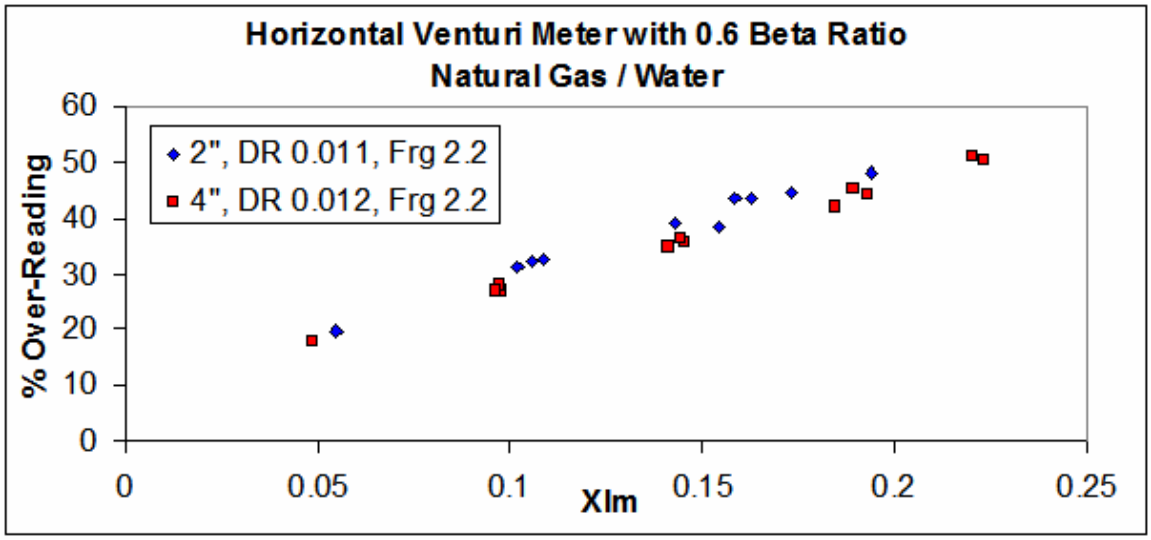

Fig 21. Diameter Comparisons for Gas / Water Low Pressure, Moderate Gas Flow Rate Data.

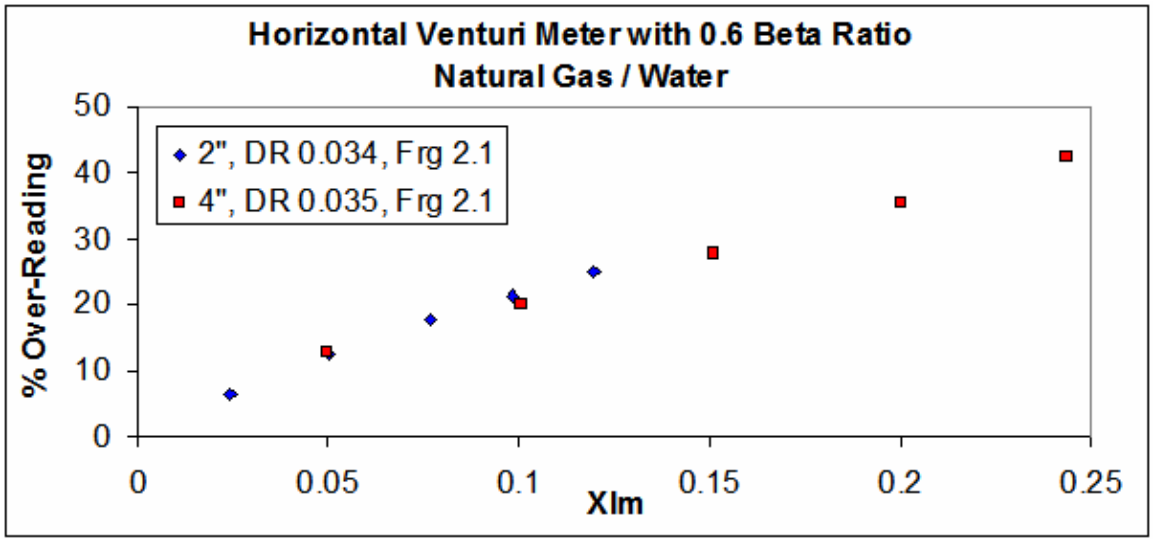

Fig 22. Diameter Comparisons for Gas / Water Moderate Pressure, Moderate Gas Flow Rate Data.

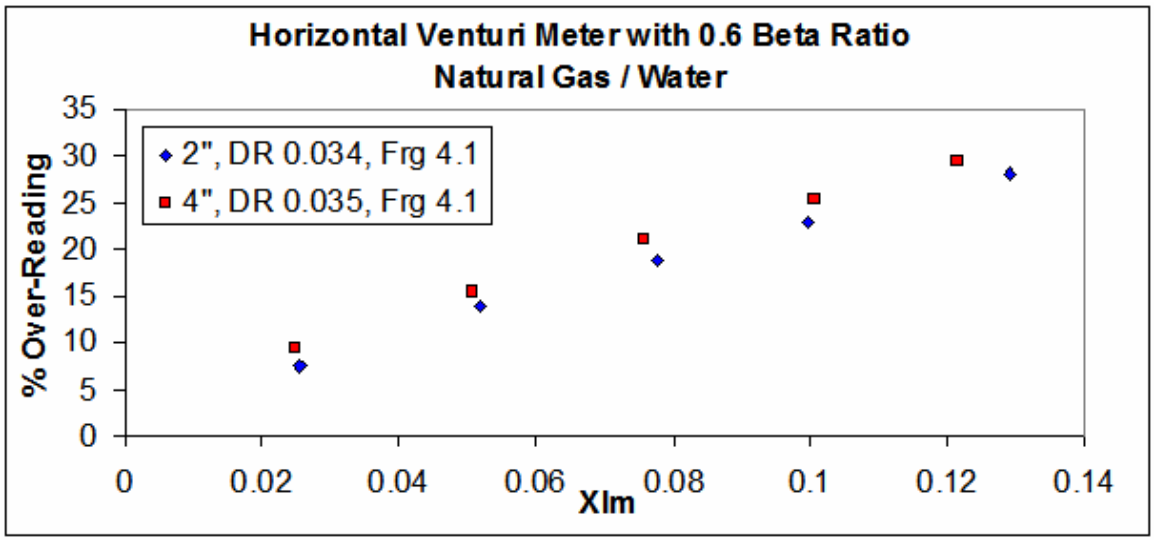

Fig 23. Diameter Comparisons for Gas / Water Moderate Pressure, High Gas Flow Rate Data.

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:

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

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:

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

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

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

Rearranging:

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

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.

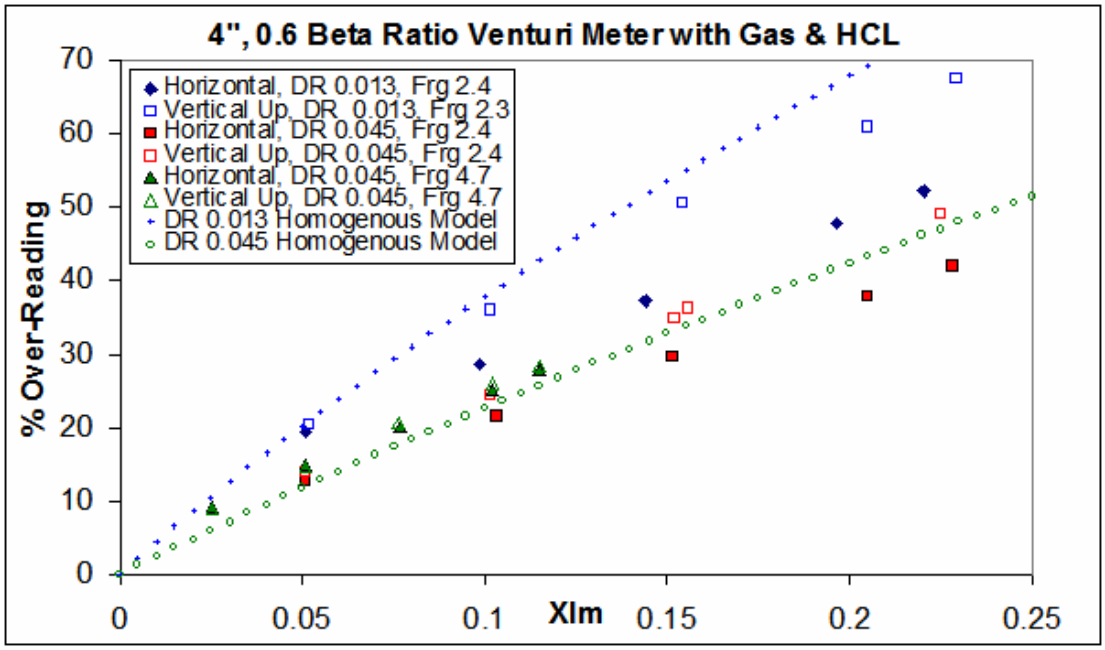

Fig 24. 4", 0.6 Beta Ratio Venturi Meter, Natural Gas & Kerosene Horizontal & Vertical Up Data.

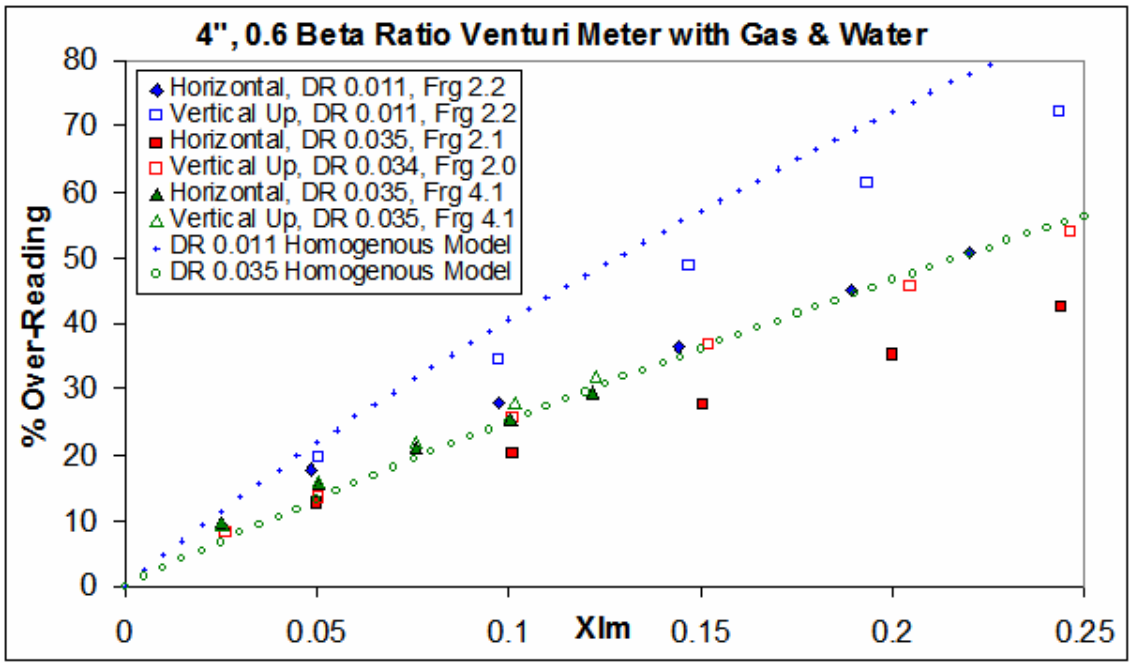

Fig 25. 4", 0.6 Beta Ratio Venturi Meter, Natural Gas & Water Horizontal & Vertical Up Data.

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.

8 REFERENCES

1. ASME MFC Guideline 19G “Wet Gas Metering”, published July 2008

2. Steven, R., “A Dimensional Analysis of Two-Phase Flow Through a Horizontally Installed Venturi Flow Meter”, Journal of Flow Measurement and Instrumentation, Article no. JFMI 536, 2008

3. Gas Processors Association., “Engineering Data Book Volume 1, Sections 1-16, Revised tenth edition”, Published 1994.

4. Taitel, Y. and Duckler, A.E., “A Model for Predicting Flow Regime Transition in Horizontal and Near Horizontal Gas-Liquid Flows”,AIChE Journal Vol 22, No.1 January 1976.

5. NEL Report 2005-206 “Venturi-Tube Performance in Wet Gas Using Different Test Fluids”.

6. Reader-Harris M., “Venturi-Tube Performance in Wet Gas Using Different Test Fluids,” North Sea Flow Measurement Workshop 2006, St Andrew’s, Scotland, UK.

7. Cazin J., Couput JP., Dudezert C., Escande J., Gajan P., Lupeau A., Strzele A., “Lessons from Wet Gas Flow Metering Systems Using Differential Measurement Devices: Testing and Flow Modeling Results”, North Sea Flow Measurement Workshop, Tonsberg, Norway, Oct 2005.

8. Reader Harris M., Hodges D., Gibson J., ”Venturi-Tube Performance in Wet Gas: Computation and Experimement”, SE Asia Hydrocarbon Flow Measurement Workshop, Kuala Lumpur, March 2007.

9. Steven. R, Britton C., Kinney J., “Liquid Property and Diameter Effects on Venturi Meters Used with Wet Gas Flows”, 6th International Symposium on Fluid Flow Measurement, Mexico 2006.

10. Steven, R., “Horizontally Installed Differential Pressure Meter Wet Gas Flow Performance Review”, North Sea Flow Measurement Workshop 2006, St Andrews, Scotland, UK.

11. Murdock. J.W., “Two-Phase Flow Measurements with Orifices" Journal of Basic Engineering, Vol.84, pp 419-433, December 1962.

12. Chisholm D., "Flow of Incompressible Two-Phase Mixtures through Sharp-Edged Orifices", Journal of Mechanical Engineering Science, Vol. 9, No.1, 1967.

13. Chisholm D., "Research Note: Two-Phase Flow Through Sharp-Edged Orifices", Journal of Mechanical Engineering Science, Vol. 19, No. 3, 1977.

14. De Leeuw R., "Liquid Correction of Venturi Meter Readings in Wet Gas Flow", North Sea Workshop 1997.

15. Stewart. D., Hodges D., Peters R., Steven R., “Wet Gas Metering with V-Cone Meters”, North Sea Flow Measurement Workshop 2002, St Andrews, Scotland, UK. Paper No.4.2.

16. Stewart D., “Application of Differential Pressure Meters to Wet Gas Flow,” 2nd International South East Asia Hydrocarbon Flow Measurement Workshop, 25th-28th March 2003.

17. Hall A., and Steven R., “New Data for the Correlation of Orifice Plate Measurements with Wet Gas Flow Conditions,” International South East Asia Hydrocarbon Flow Measurement Workshop, March 2007.

18. Steven R., Ting V.C., Stobie G., “A Re-Evaluation of Axioms Regarding Orifice Meter Wet Gas Flow Performance,” International South East Asia Hydrocarbon Flow Measurement Workshop, March 2007.

19. Steven R., Hall A., Stobie G., “Further Evaluation of the Performance of Horizontally Installed Orifice Plate and Cone Differential Pressure Meters with Wet Gas Flows”, International South East Asia Hydrocarbon Flow Measurement Workshop, March 2008.

20. Jamieson, A., “Key Note - Status and Trends in Technology and Applications”, North Sea Flow Measurement Workshop 2001, Kristiansand, Norway

21. Steven R., “V-Cone Wet Gas Metering,” North Sea Flow Measurement Workshop, Oslo, Norway, 2007.

North Sea FLOW Measurement Workshop

Paper 7.3

Measurement of the Liquid Water Flow Rate Using Microwave Sensors in Wet-Gas Meters: Not As Simple As You Might Think

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Measurement of the Liquid Water Flow Rate Using Microwave Sensors in Wet-Gas Meters: Not As Simple As You Might Think

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1 INTRODUCTION

The development of off-shore natural gas fields is demanding because the equipment is not readily accessible. One of the challenges is the prevention of wax and scale deposition and hydrate formation. The latter two problems are related to the water production of the wells and because the capacities of the scale and hydrate inhibition systems are limited, it is essential for the flow assurance that the water flow rate is measured for inhibition dosage. To that end, several wet-gas flow meters are able to measure the water flow rate as a separate parameter. One of the techniques, which is applied in several wet-gas meters, uses microwaves to determine the water flow rate.

At first sight, the technique seems rather straightforward and as the relative dielectric constant of liquid water is roughly 81, one would expect that such systems have a high sensitivity for liquid water. Unfortunately, the situation is more complex than this and under realistic conditions, the contribution of the liquid water is only a minute fraction of other contributions, the major one – surprisingly- being the gas itself. This leads to severe complications and in this paper we will discuss the different contributions to the microwave reading and the consequences for the scale and hydrate inhibition systems.

2 THE PRINCIPLE OF THE WATER FLOW RATE MEASUREMENT USING THE MICROWAVE TECHNIQUE

A wet-gas meter in a well flow line has to cope with the following three contributions to the total water flow rate:

1. The water vapour in the gas
2. Liquid water, due to condensation of water vapour from the gas
3. Formation water, liquid by nature, usually carrying minerals

Ad 1.

In most cases, the gas in the reservoir is saturated with water vapour at the initial pressure and temperature[1] because the gas is in contact with an aquifer. When produced, the gas temperature and pressure drop which mostly results in the condensation of a part of the water vapour. At meter conditions, the gas is therefore still saturated with water vapour, but a part has condensed. When the meter is close to the well, the pressure and temperature are usually so high that the water vapour flow is still a major contributor to the water flow rate when no or little formation water is produced. Using PVT simulation, the water vapour molar fraction in the gas can be estimated accurately, provided the pressure and especially the temperature at the meter are measured with a high accuracy. The temperature is so important because the water vapour partial pressure increases exponentially with temperature (the water vapour molar fraction in the gas increases by more than 4% / K), as is illustrated in fig. 1. Unfortunately, the contribution of water vapour to the primary measurement is significantly stronger than the contribution of the same amount of liquid water in mass terms. This will be discussed in more detail in sec. 2.3.

[1] Initial means before production started.

Ad 2.

Part of the water vapour from the reservoir condenses due to the lower pressure and temperature at the meter. Provided the initial pressure, temperature and composition of the reservoir are well known, the initial water vapour molar fraction in the reservoir can be calculated using PVT simulation and by subtracting the water vapour molar fraction at the meter (see above), the condensed water flow rate can be calculated. The uncertainties in this calculation are the initial temperature in the reservoir and the possibility that water vapour is supplied by e.g. connate water when the pressure in the reservoir drops, thus increasing the water vapour molar fraction in the gas gradually over field life.

Ad 3.

As most reservoirs are in contact with an aquifer, it is possible to produce water from this aquifer together with the gas. There is no way to predict the formation water flow rate from PVT or by any other means, so it is necessary to measure this flow rate in one way or another.

So we have two uncertain contributions to the liquid water flow rate, being the condensed water flow rate, which could be influenced by the presence of connate water (and thus gradually increase over field life), and the formation water flow rate. The microwave technique should enable the measurement of the liquid water flow rate. This is not trivial and therefore we will have to look deeper into the physical principles of the technique. We will see that the contribution of the liquid water to the primary measurement is only very small compared to other contributors. But in order to understand this, we will need to get a deeper understanding of the measurement principles and how the primary measurement depends on the different parameters.

2.1 The Microwave Technique

A simple description of the microwave technique is as follows: an antenna sends out microwave radiation into a cavity, created in some way in the flow line. At a certain frequency, the wavelength of the microwave radiation "fits" in the cavity, which starts to act as a resonator (a bit similar to a pipe in an organ). This frequency is therefore a characteristic of the cavity. But not only of the cavity: also the electrical and magnetic properties of the fluids which fill the cavity (i.e. the produced fluids!) play a role. Regarding the physical properties of the fluids, the magnetic properties can be taken the same as those of vacuum; the electrical properties, however, are a different story. The well fluids are polarizable and thus influence the dielectric constant of the medium, filling the cavity. Both the magnetic and electrical properties of the fluids in the cavity determine the velocity of electromagnetic waves. In equations:

$$c = \frac{1}{\sqrt{\varepsilon\,\mu}} \qquad (1)$$

in which:

c	=	velocity of light	m/s
ε	=	dielectric constant	As/Vm or A^2s^4/kgm^3
μ	=	magnetic permeability	Vs/Am or kgm/A^2s^2

The dielectric constant of a medium is usually expressed as:

$$\varepsilon = \varepsilon_r\,\varepsilon_0 \qquad (2)$$

in which:

ε_r	=	relative dielectric constant	
ε_0	=	dielectric constant of vacuum	As/Vm or A^2s^4/kgm^3

The specific electrical properties of a medium can thus be captured in ε_r which always ≥ 1. Therefore, we will use ε_r from here on. Knowing that

$$f_{r,v} = \frac{c}{\lambda} \qquad (3)$$

in which:

$f_{r,v}$	=	resonance frequency of the cavity in vacuum	Hz
λ	=	wavelength, determined by the geometry of the cavity	m

it is not hard to combine the above equations to obtain:

$$f_{r,m} = \frac{c_v}{\lambda\sqrt{\varepsilon_r}} = \frac{f_{r,v}}{\sqrt{\varepsilon_r}} \tag{4}$$

in which:

c_v	=	velocity of light in vacuum	m/s
$f_{r,m}$	=	resonance frequency of the cavity filled with one or other medium	Hz

The resonance frequency thus decreases with an increase of the relative dielectric constant of the medium, filling the cavity. Therefore, by measuring the (change of the) resonance frequency when the cavity is filled with a medium, the relative dielectric constant of the medium can be determined. The determination of the resonance frequency is the primary measurement of the technique. Unfortunately, this primary measurement is not only dependent on the liquid water water flow rate, because in the case of wet-gas, the relative dielectric constant is a function of the gas composition, pressure & temperature, the condensate dielectric constant & volume fraction, the water density & volume fraction and the distribution of the liquids over the cross sectional area. So basically, by the determination of the ε_m, the relative dielectric constant of the mixture in the cavity, one can get information about the mixture, albeit in a complicated way and with contributions from the gas and condensate. The latter contributions will show to be dominant. To shed some light on this complex matter, we will study it step-by-step to gain insight in the different contributions. We will start off with the ε_g, the relative dielectric constant of the gas.

2.2 The Depedencies of ε_g on the Gas Properties

The gas basically acts as a dielectricum, similar as the dielectricum in a capacitor. One can understand that the effect is smaller than with a "normal" dielectricum, because far less molecules are present in a gas, compared to a solid. But it is also easy to see that there will be a dependence on the pressure and temperature, because these parameters determine the amount of molecules per unit volume. Also, it is reasonable to assume that the type of molecule is of importance. Quantitatively, for low pressures, the ε_g is described by the Clausius - Mossotti equation:

$$\frac{\varepsilon_g - 1}{\varepsilon_g + 2} = \frac{1}{3} \mathrm{N}_m \alpha_m \tag{5}$$

in which:

N_m	=	Number of molecules per unit volume	m^{-3}
α_m	=	Specific property of the molecule, often larger for polar substances	m^3

From this equation, it is easy to see that if $\varepsilon_g \ll 3$, then ε_g -1 is roughly proportional to the density and thus the pressure for a specific gas. Using this equation to determine the α_m for some substances, the following table has been compiled:

Table 1: The Constant to Estimate the Relative Dielectric Constant for Different Substances.

Component	Constant (ppm/bar[2])
Methane	944
Ethane	1500
n-Pentane	2500
Carbon dioxide	990
Water vapour	12600

[2] To avoid small numbers, the figures are equal to 10^6 (ε_g - 1), ε_g measured at 1 bar.

Although the information in Table 1 is rather sketchy, some trends can be distinguished. The polarizability of the alkanes increases with C-number, which is not surprising as their electron cloud will be more extended and will deviate more from spherical with increasing C-number. Also, the water molecule, which is a dipole, is significantly more polarizable than the alkane molecules. This is the same in liquids, liquid water has a relative dielectric constant of 81, whereas hydrocarbon condensates have relative dielectric constants in the range 1.5 - 2.5, depending on the composition as will be discussed in sec.2.4.

From fig. 2, using the data from [1], it can also be seen that the constants differ strongly for different substances. Also, closer examination reveals that the Clausius - Mossotti equation is not exact at elevated pressures, because it does not take the molecular interaction into account. The deviations for elevated pressures are illustrated in fig. 3, where the Ethane behaviour is illustrated when the low pressure constant (ppm/bar) is used to remove the slope. If ε_g - 1 would be proportional to the pressure, the whole curve would have collapsed to a constant at the value of 1. But above 15 bar, the deviations become very clear and can no longer be neglected. When the pressure is replaced by the density to correct for compressibility effects, still deviations occur as is illustrated in fig. 4. Later on we will see that these deviations are not negligible either, even though these seem small at first sight. Similarly, the Clausius - Mossotti equation is not exact for mixtures, again because of the molecular interactions [2]. From table 1 and figs. 2, 3 and 4, some important conclusions can be drawn:

- With constant composition, ε_g usually does not depend linearly on the density.
- When different substances are compared, ε_g does not uniquely depend on the density. Compare e.g. Ethane (mol. weight = 30) with Carbon Dioxide (mol. weight = 44).
- Because of the above, ε_g is hard to predict outside the calibration range of pressure and temperature for a given gas composition.
- Because of the above, ε_g is hard to predict for gases with a different composition.

As has been shown above, it is not easy to predict accurately the ε_g and as the ε_m is determined mainly by the ε_g as we will see shortly, the question is how errors in the determination of ε_g "translate" into errors in the liquid water flow rate. This problem is enhanced by the contribution of the condensate. To estimate these, we need to study the effect of liquids on the ε_m. This is, however, not simple either.

2.3 The Liquid Contributions to ε_m

Because of the complexity of gas-liquid systems, we will start with a simplified system first. Assume that the liquids are distributed homogeneously as small spherical droplets in the gas, so the gas is the "continuous" phase, see fig. 5. Regarding the condensate and water flow rates in high pressure wet-gas flows, this last assumption is valid in many cases, but should be verified in each individual case. The first model which springs into mind is that the ε_m is the volume weighted avarage of the ε_g and the ε_l, similar to the average density of a mixture:

$$\varepsilon_m = (1-\phi_l)\varepsilon_g + \phi_l \varepsilon_l \tag{6}$$

But this is unrealistic: the droplets influence the field lines and reduce the voltage drop over their own diameter, but these effects contribute far less than eq. [6] predicts. To get a more realistic number, the “stratified” model can be used: all the liquid is brought as a thin layer to one of the capacitor plates and then the total capacitance can be calculated as a series of two capacitors, one filled with gas and one filled with liquid, as is illustrated in fig. 6. The outcome is

$$\varepsilon_m = \frac{\varepsilon_g\, \varepsilon_l}{(1-\phi_l)\,\varepsilon_l + \phi_l\, \varepsilon_g} \tag{7}$$

in which:

ε_m = relative dielectric constant of mixture
ε_l = relative dielectric constant of liquid

ε_g = relative dielectric constant of gas
ϕ_l = liquid volume fraction

The difference between the outcome of the two models is illustrated in fig. 7 when water is taken as liquid. The predictions of the proportional model are far larger than those of the stratified model and further analysis shows that the differences are far smaller with condensate with an ε_c of 2. This is because the stratified model predicts a saturation effect, which is easy to understand: the liquid filled capacitor is in series with the gas filled capacitor, so even if this capacitance would be infinite, the gas filled capacitor would limit the total capacitance, as can be seen from fig. 8. The proportional model does not predict such a saturation, but looking at the distribution of the liquid, it should level off with increasing ε_l. This is a disadvantage for this specific application as this reduces the sensitivity for water; a phenomenon which will be discussed in more detail later.

It is obvious that both models are gross simplifications of reality and in the previous century, more sophisticated models of such systems have been made. A model, which describes the ε_m of a homogeneous mixture with a low volume fraction of liquid well, is the the Bruggeman model. It is outside the scope of this study to go into the details of the derivation. Although other models exist, there is general agreement that the Bruggeman model works well for low liquid volume fractions (LVF's). The equation, which holds both for water and condensate is:

$$\left(\frac{\varepsilon_w - \varepsilon_m}{\varepsilon_w - \varepsilon_g}\right)\left(\frac{\varepsilon_g}{\varepsilon_m}\right)^{A_a} = 1 - \phi_w \qquad (8)$$

in which:
ε_w = relative dielectric constant of water
ε_m = relative dielectric constant of the mixture
ε_g = relative dielectric constant of the gas
A_a = shape factor (= 1/3 for spherical droplets)
ϕ_w = water volume fraction

As this is an implicit equation, it needs to be solved iteratively, which is not very complicated.

The value of ε_g has been discussed in the previous section and as the largest molar fraction of the gas is Methane, we will use as a typical value @ 100 bar ε_g = 1.10 (see Table 1), which should not be too far out. And for the determination of the sensitivity on the different parameters, it is not really essential.

Now assume that an accurate value for the relative dielectric constant of the gas is available, say the above mentioned 1.100 @ 100 bar. First, two-phase mixtures are studied, either gas-water (ε_r = 81) or gas-condensate (ε_r = 2). When these values are used to solve the Bruggeman equation, the following results are obtained:

Table 2: The Effects of the Presence of a Homogeneous Liquid Mist in the Gas, Based on the Bruggeman Equation.

LVF (%)	ε_m (water)	$\varepsilon_m - \varepsilon_g$	ε_m (cond)	$\varepsilon_m - \varepsilon_g$	Δ_w / Δ_c
0.1	1.103175	0.003175	1.100707	0.000707	4.49
0.3	1.109561	0.009561	1.102123	0.002123	4.50
0.5	1.115996	0.015996	1.103540	0.003540	4.52
0.7	1.122479	0.022479	1.104959	0.004959	4.53
1.0	1.132290	0.032290	1.107090	0.007090	4.55

From Table 2, two aspects become clear. First of all, the effect is -at these small LVF's- very close to proportional to the LVF for a given liquid and -surprisingly- the effect of water is less than five times the effect of condensate, even though its dielectric constant is 40 (!) times higher. The Bruggeman equation, based on the homogeneous distribution of small droplets, is not so

easy to understand, but some of the above mentioned effects can be qualitatively understood by a the stratified model.

In fig. 9, three different models are shown. The simple proportional model, the stratified model and the Bruggeman model. For very small values of ε_l - ε_g, the three curves coincide, above that, the stratified model deviates stronger from the proportional model than the Bruggeman model as illustrated in fig. 10. However, also for the latter the effect is smaller than LVF · ($\varepsilon_{w,c}$ - ε_g). This is related to the above mentioned saturation effect, which will be discussed in more detail in paragraph 2.4. As a first approximation, the effect of 0.1 vol% of liquid water is about the same as a change in pressure of the gas of 3 bar @ 100 bar. In other words, an error of 1% in the gas pressure reading @ 100 bar alone results in an error of the liquid water volume fraction of 0.033%. This makes clear that the actual relative dielectric constant of the gas needs to be known with a very high accuracy in order to determine the liquid water volume fraction.

2.4 The Condensate Contribution

The contribution of the condensate has already been mentioned in the previous section, but the relative dielectric constant was taken as 2. However, from literature, it is clear that the relative dielectric constant of liquids depends on their composition [5]. Although there seems to be a unique relation between density of alkanes and their relative dielectric constant, it is not certain that this relation holds for e.g. aromates and/or at elevated pressure and temperature, when a large molar fraction of the condensate consists of light alkanes like Methane and Ethane (**N.B.** In the example below, the molar fraction of C_1 and C_2 in the condensate is roughly 40%, whereas in the liquids, used for the determination of the ε_c correlation, it is next to zero). The contribution of the condensate to ε_m, however, strongly depends on the ε_c, as is illustrated in fig. 11. As a first approximation, the contribution is proportional to (ε_c - ε_g). This enhances errors in the value of ε_c significantly. Note that the relation is not completely linear and the deviations increase with increasing value of ε_c as is illustrated in fig. 12. The reason is that the effect saturates: the electric field lines will tend to concentrate in the droplets because these have a higher relative dielectric constant. The higher the value of the ε_c, the more the field lines will tend to creep into the droplets, but there is a limit to this. Once all the field lines move through the droplets, there is nothing more to achieve, so the effect saturates and when the droplets consist of water, virtually all the electric field lines go through the droplets. As a result, the ε_m does not increase significantly when $\varepsilon_c > 20$, as can be seen from fig. 13, and therefore the ratio between the water and condensate contributions (see table 2) is far smaller than the ratio of their relative dielectric constants.

2.5 The Sensitivity of ε_m for the Shape Factor A_a

The sensitivity of ε_m for A_a can be derived from the Bruggeman equation. But as this is an implicit equation, some approximations need to be made. Assuming that $\varepsilon_w \gg \varepsilon_g$ and $\varepsilon_g \approx \varepsilon_m$, the Bruggeman equation can be approximated by:

$$\left(\frac{\varepsilon_w - \varepsilon_m}{\varepsilon_w - \varepsilon_g}\right)\left(\frac{\varepsilon_g}{\varepsilon_m}\right)^{A_a} \approx \left(\frac{\varepsilon_g}{\varepsilon_m}\right)^{A_a} = 1 - \phi_w \tag{9}$$

Using $\varepsilon_g = \varepsilon_m - \Delta\varepsilon$ and $\Delta\varepsilon \ll \varepsilon_g$, the Taylor series development gives:

$$\left(\frac{\varepsilon_m - \Delta\varepsilon}{\varepsilon_m}\right)^{A_a} \approx 1 - A_a\left(\frac{\Delta\varepsilon}{\varepsilon_m}\right) = 1 - \phi_w \tag{10}$$

Assuming ϕ_w « 1, the result is:

$$\Delta\varepsilon = \frac{\phi_w \varepsilon_g}{A_a} \tag{11}$$

which means that $\Delta\varepsilon$ is inversely proportional to A_a. As the shape factor can vary from $^1/_3$ (spheres) to $^1/_2$ (needles), the effect is strong. The complexity is further enhanced by the probably more or less random orientation of the major axis of the non-spherical droplets. Note that these assumptions are valid for water, but not for condensate. As a result, the primary measurement is more sensitive for the shape factor of water droplets than for the shape factor of condensate droplets.

2.6 The Sensitivity of ε_m for the Slip Velocity between the Gas and Droplets

The liquid, dispersed as droplets in the gas phase, usually moves slower than the gas. This is a bit paradoxical, because one would expect that the gas would accelerate the droplets until they have reached the gas velocity. But this phenomenon can be understood in the following way: due to the turbulence, the droplets move around chaotically in the flow and ever so often they hit the wall, where they stick. Due to the large velocity gradients between the liquid and the wall, the liquid decelerates quickly, creating (a part of) the pressure drop in the flow line. On the other hand, the large velocity difference between the gas and the liquid film at the wall creates a very high shear, which tears of drops from the liquid layer. These drops are subsequently accelerated by the gas until they again hit the wall. Due to this phenomenon, the liquid, dispersed as drops, moves -on average- slower than the gas and there is always a liquid layer at the wall, which moves far slower than the gas. These two liquid fractions do, however, have significant different effects on the microwave unit.

The ε_m is not determined by the LVF, but by the amount of liquid, dispersed in the cavity. Therefore, on the one hand, the slip velocity of the droplets creates a larger effect than can be expected, based on the LVF alone. The actual concentration is increased by a factor which is equal to v_g / v_d in which v_g is the actual average gas velocity and v_d is the actual average droplet velocity. By definition, v_g - v_d is the slip velocity. On the other hand, the entrained fraction is never 100%, which reduces the contribution. In equation:

$$\Delta\varepsilon_a = \frac{v_g}{v_d}\Delta\varepsilon_{LVF}\,E_f = \frac{v_g}{v_g - v_s}\Delta\varepsilon_{LVF}\,E_f \tag{12}$$

in which:

$\Delta\varepsilon_a$	=	contribution of droplets to ε_m under actual conditions	
v_g	=	gas velocity	m/s
v_d	=	droplet velocity	m/s
v_s	=	slip velocity	m/s
$\Delta\varepsilon_{LVF}$	=	contribution of droplets to ε_m based on LVF	
E_f	=	Entrained fraction	

This equation makes clear that the modelling of the multi-phase flow plays an essential part in the calculations. In principle, it could also be calibrated, but this has its own problems, as will be discussed later.

2.7 The Sensitivity of ε_m for the Liquid Film at the Wall

The liquid at the wall is not interacting in the same way as the liquid, dispersed as droplets. The question is whether it interacts at all. It is in contact with a conducting wall and therefore, it is likely to behave differently. It is not unlikely that the contribution of the liquid film should probably be subtracted from the total liquid contribution. Because of the high relative dielectric constant of water, a water film is more likely to behave this way than condensate.
N.B. Equation [12] in sec. 2.6 describes in that case the total contribution to the ε_m.

However, there is another effect, which could play a role: the liquid film at the wall might change the dimensions of the cavity (compare with the simple "stratified" model) and therefore, it could indirectly influence the result. If it is assumed that λ is constant, a change in λ could result in an apparent change in ε_m:

$$\Delta \varepsilon_{app} = \frac{2\,\Delta\lambda}{\lambda}\,\varepsilon_m \tag{13}$$

in which:

$\Delta\varepsilon_{app}$ = apparent change in ε_m due to the change $\Delta\lambda$ of the cavity.
$\Delta\lambda$ = change in length of resonant cavity due to liquid at the wall
m

N.B. The factor of 2 is caused by the square relation between λ and ε_m, see eqs. [3] and [4]. Also in this case, water is likely to be more effective than condensate.

3 DISCUSSION

The actual question is how the different contributions relate to one another. Of course, this depends strongly on the actual composition of the reservoir fluids, the pressure and temperature downhole and the pressure and temperature at the meter. We will give a representative example, but it should be clear that this is only an example and with different gas fields, the actual situation will be different. The composition we used is from a test-loop in which we did some experiments a few years ago, the initial reservoir pressure and temperature have been set at 210 bar and 100 ^{o}C with saturated water vapour and no down-hole condensation (neither of water nor of hydrocarbons). The meter conditions have been chosen to be 100 bar and 70 ^{o}C. As a result of the latter, the WVF at the meter is 0.0282%, the CVF is 3.52% and the Lockhart-Martinelli parameter is almost 0.1, so a typical wet-gas condition. The contributions to the microwave resonance frequencies, expressed as (ε - 1) are presented in fig. 14. As the liquid water contribution is hardly discernable, the same data are presented in fig. 15 where vertically a logarithmic scale is applied. It is clear that the gas contribution is roughly two orders of magnitude larger than the liquid water contribution and the condensate contribution is roughly 20 times as high. Slight errors in either (or both) of these estimates will easily outshine the liquid water contribution.

The obvious question is whether these effects can simply be calibrated in a test-loop. This, too, is not as simple as it might seem because there are severe limits to the possibilities of calibration. This will be discussed in the next section.

4 THE LIMITS TO CALIBRATIONS

The available test-loops have only a limited operational envelope. K-lab, Norway, is one of the best, but it cannot operate above approx. 120 bar and 70 ^{o}C. So first of all, the operational envelope of the test-loops prohibits that all P&T conditions are calibrated.

The second major issue is that the number of test-points cannot grow unlimited. In the case of a recent development, the following independent parameters have been be identified:

1. Pressure
2. Temperature
3. Gas composition
4. CVF
5. WVF
6. Gas velocity
7. Salinity

Maybe some other parameters could be included, but even with the above and using 5 points per dimension (which is not excessive), the total number of test-points would end up at 78125, which is unrealistic.

This problem could be mitigated if we were able to "translate" the test-loop conditions to the actual conditions (so including pressure, temperature, gas composition and relative dielectric constant of the condensate). But this is unlikely: the accuracy of the PVT simulation for the prediction of properties like densities is commonly estimated to be around 2% at elevated pressure (say, 100 bar and above), but the prediction of the *electrical* properties of the fluids is not included. And as we have seen, density and ε_g are not directly related. This is illustrated by another example: we replace 2 mole % of Methane by 2 mole % of Carbon Dioxide in the reservoir stream. As Methane and Carbon Dioxide have virtually the same contribution per molecule (see table 1), this will not influence the gas contribution to the ε_m notably, but the gas density will increase by almost 3.5%. If we would assume that the gas contribution is proportional to the density, we would assume an increase of the ε_g of 3800 ppm, more than 4 times the liquid water contribution to ε_m! Added to this concern is the influence of water vapour, which partial pressure increases exponentially with temperature, as is illustrated in fig. 1. Because the water vapour contributes far more to the ε_m than the same amount of water as liquid, this rapid change of the water vapour fraction could give rise to serious errors when the pressure and temperature are not measured with a very high accuracy. Note also that water vapour contributes per molecule 13 times as much as methane, even though their molecular weights are about the same.

The major consequence of these limitations is that the microwave technique can not in all cases provide sufficiently accurate liquid water flow rates for the optimum injection of hydrate and scale inhibitors. Other ways might have to be found and used in each specific application. This is an essential limitation on this approach, a direct consequence of basic physics.

5 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Conclusions

1. The microwave technique to determine the water flow rate is hampered by the sensitivity of the reading by the relative dielectric constants of the gas and the condensate and the condensate volume fraction. These contributions are far larger (100, resp. 20 times in a realistic example) than the liquid water contributions.

2. The accuracy of the determination of the gas and condensate contributions depends on the accuracy of the measurements of pressure and temperature at the meter and the availability of a detailed and accurate composition. Especially the rapid change of the water vapour partial pressure with temperature requires an accurate temperature measurement.

3. The "translation" from test-loop to actual conditions is not trivial as the relative dielectric constant of gas is not uniquely related to "simple" physical properties like density. In most cases, it cannot be done with sufficiently high accuracy to predict the liquid water flow rate without an in-line calibration.

4. The condensate contribution to the reading of the microwave system is a strong function of the relative dielectric constant of the condensate. Little is known about this property under realistic conditions when small alkanes (e.g. Methane and Ethane) make up a large molar fraction of the condensate and with different types of molecules (e.g. aromates).

5.2 Recommendations for Future Work

1. The relative dielectric constant of hydrocarbon liquids at high pressures and temperatures, as occur in wet-gas flows, so including high molar fractions of e.g. Methane and Ethane, should be determined experimentally.

2. PVT simulators should be extended to include the electrical properties of gas mixtures at wet-gas well flow conditions in order to enhance the "translation" from test-loop to actual conditions.

3. The distribution of the liquids in wet-gas flows and the slip velocities should be studied both experimentally and theoretically to improve the interpretation of the microwave measurement results.

6 REFERENCES

[1] J.W. SCHMIDT and M.R. MOLDOVER, "Dielectric Permittivity of Eight Gases Measured with Cross Capacitors", International Journal of Thermophysics, Vol. 24, No. 2, March 2003, pp. 375 - 403.

[2] JEAN- MARIE St-ARNAUD, RICHARD OKAMBAWA, TAPAN K. BOSE and OLIVIER le NOË,"Comparison between a Pressure-Volume-Temperature Method (Z Meter) and the Dielectric Constant Method: Applications to the Compressiblity Factor of Five Gaseous Mixtures", High Temperatures – High Pressures, Vol. 29, 1997, pp. 461 – 466.

[3] D.A.G. BRUGGEMAN, "Berechnung verschiedener physikalischer Konstanten von Heterogenen Substanzen. I. Dielektrizitätskonstanten und Leitfähigkeiten der Mischkörper aus Isotropen Substanzen", Annalen der Physik, 5. Folge, Band 4, 1935, pp. 636 - 668.

[4] AUDUN ASPELAND et. al., "Measuring Multiphase Flow in a Pipe", United States Patent US 6,655,221 B1 (Dec. 2, 2003)

[5] Handbook of Chemistry and Physics, 64th edition. CRC press 1983 – 1984.

A_a	=	shape factor (= 1/3 for spherical droplets)	
c	=	velocity of light	m/s
E_f	=	Entrained fraction	
$f_{r,m}$	=	resonance frequency of the cavity filled with one or other medium	Hz
$f_{r,v}$	=	resonance frequency of the cavity in vacuum	Hz
N_m	=	Number of molecules per unit volume	m^{-3}
v_d	=	droplet velocity	m/s
v_g	=	gas velocity	m/s
v_s	=	slip velocity	m/s
α_m	=	Specific property of the molecule, often larger for polar substances	m^3
$\Delta\varepsilon_a$	=	contribution of droplets to ε_m under actual conditions	
$\Delta\varepsilon_{app}$	=	apparent change in ε_m due to the change $\Delta\lambda$ of the cavity.	
$\Delta\varepsilon_{LVF}$	=	Contribution of droplets to ε_m based on LVF	
$\Delta\lambda$	=	change in length of resonant cavity due to liquid at the wall	m
ε	=	dielectric constant	As/Vm or A^2s^4/kgm^3
ε_0	=	dielectric constant of vacuum	As/Vm or A^2s^4/kgm^3
ε_g	=	relative dielectric constant of the gas	
ε_l	=	relative dielectric constant of liquid	
ε_m	=	relative dielectric constant of the mixture	
ε_r	=	relative dielectric constant	
ε_w	=	relative dielectric constant of water	
ϕ_l	=	liquid volume fraction	
ϕ_w	=	water volume fraction	
λ	=	wavelength, determined by the geometry of the cavity	m
μ	=	magnetic permeability	Vs/Am or kgm/A^2s^2

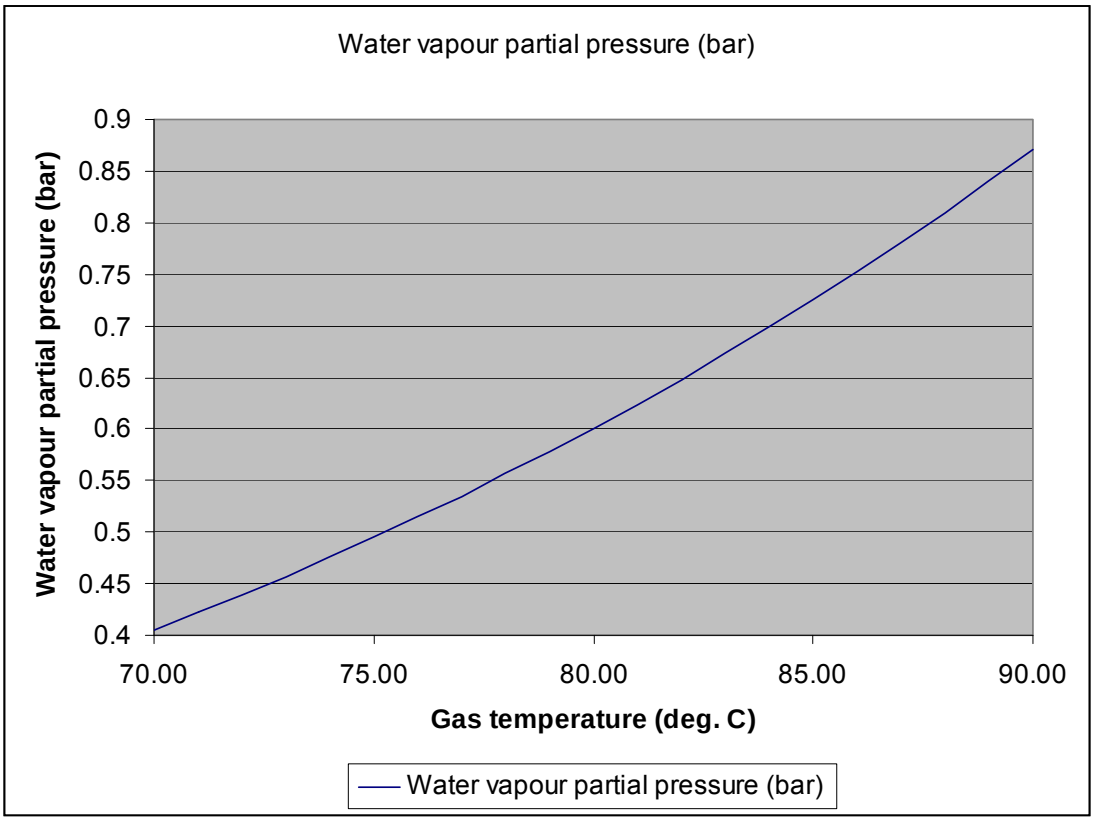

Figure 1: The water vapour partial pressure as a function of temperature. Note the exponential increase (more than a factor of 2 over 20 K), which makes the contribution to ε_r sensitive to temperature measurement errors.

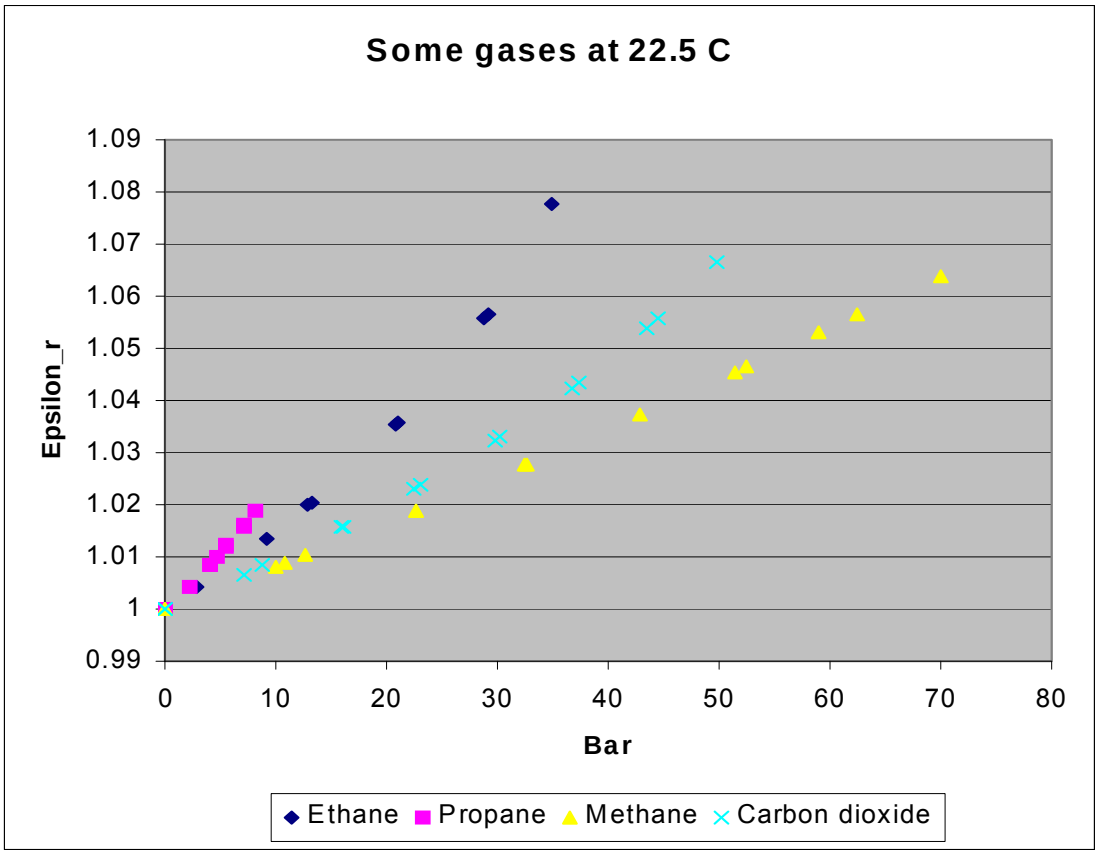

Figure 2: The ε_r of different gases as a function of pressure. Note the non-linear response of especially Ethane and Carbon dioxide.

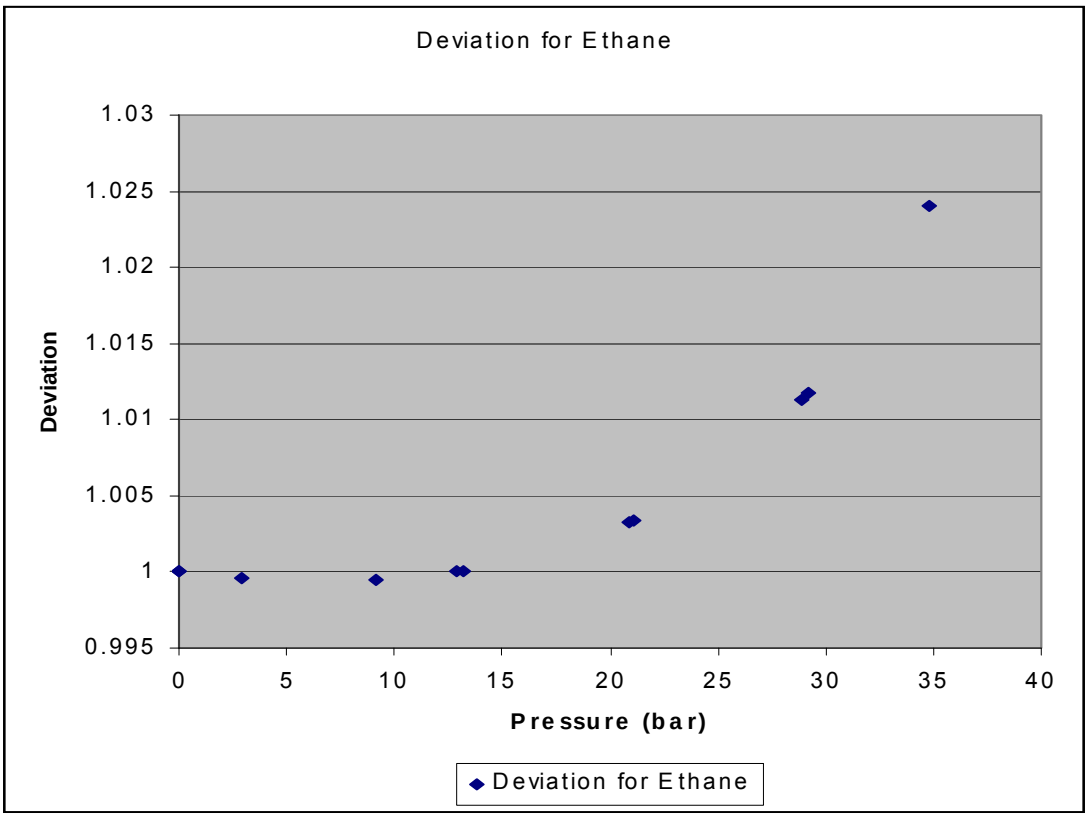

Figure 3: The deviation from a linear response of Ethane (see also fig. 2). The slope in the range from 0 – 15 bar has been removed to enlarge the non-linear behaviour above 15 bar.

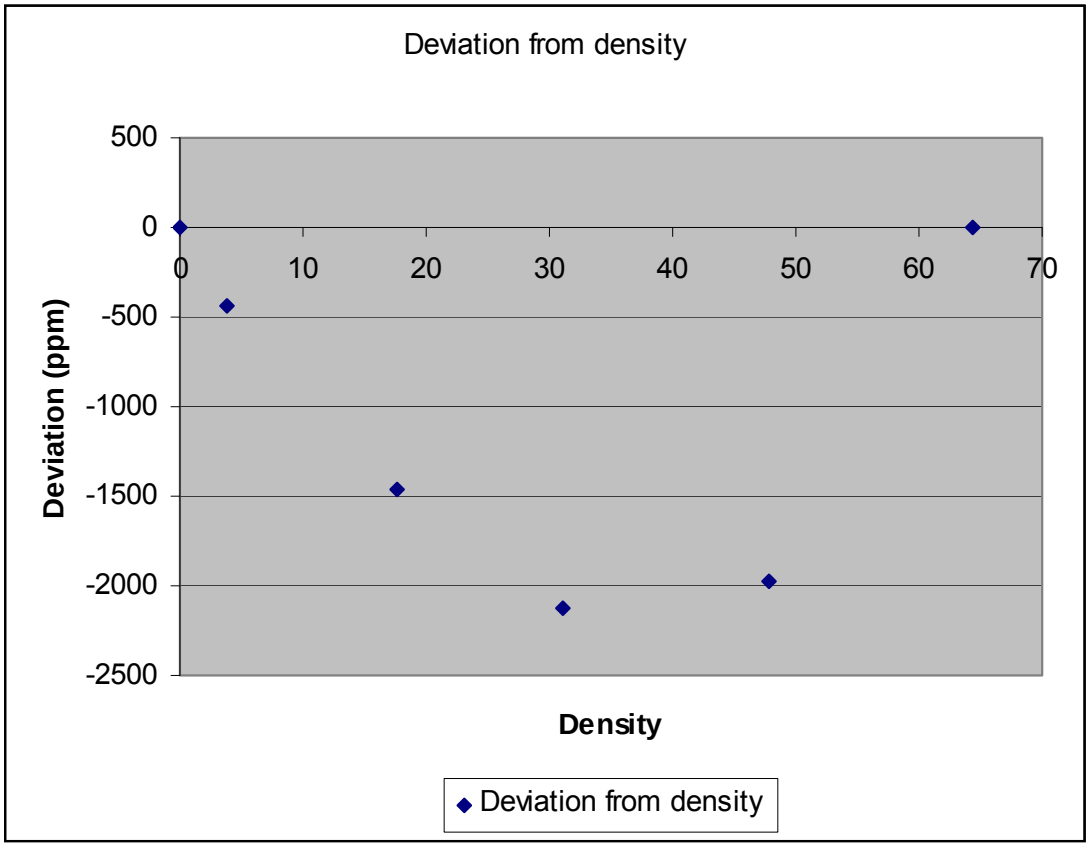

Figure 4: The deviation from a linear response of Ethane (see also fig. 3), plotted against density instead of pressure to correct for the compressibility of Ethane. The values at 0 bar and 35 bar have been used as references.

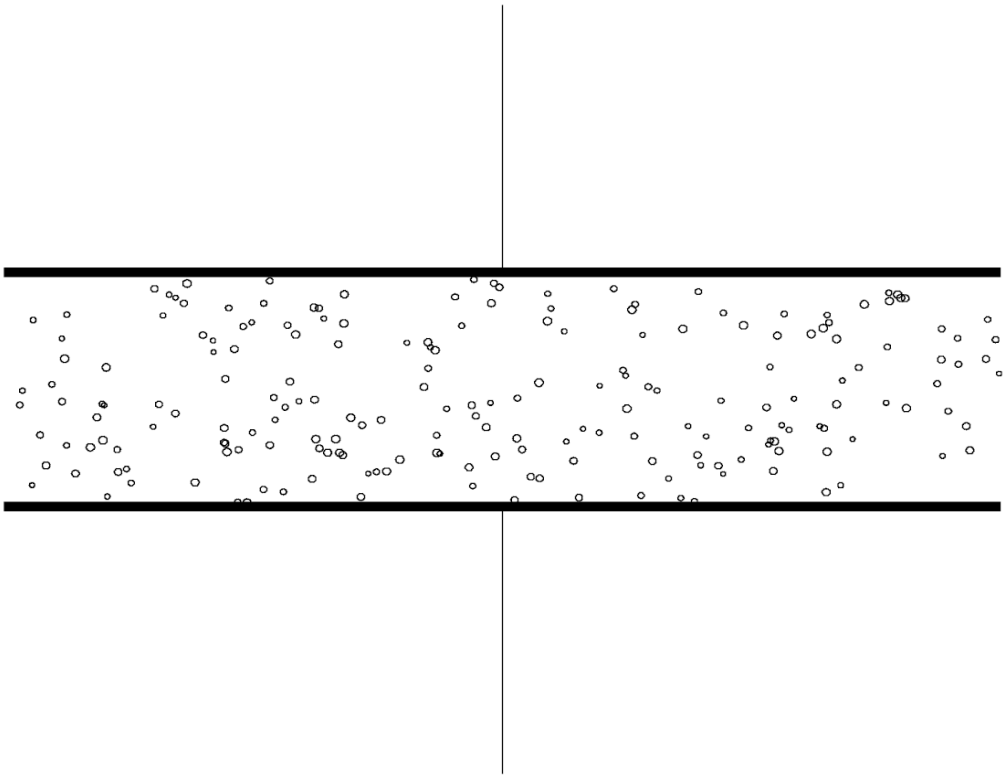

Figure 5: The droplets in a capacitor will influence the capacitance.

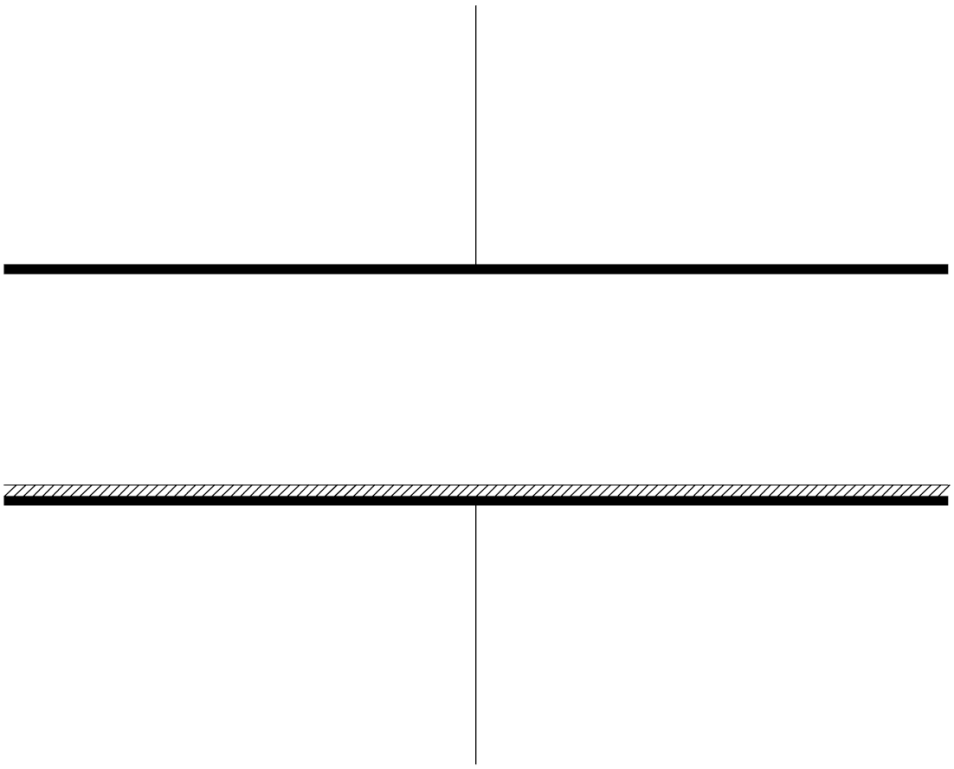

Figure 6: As an approximation, all the liquid will be assumed to be in a thin layer at one of the plates.

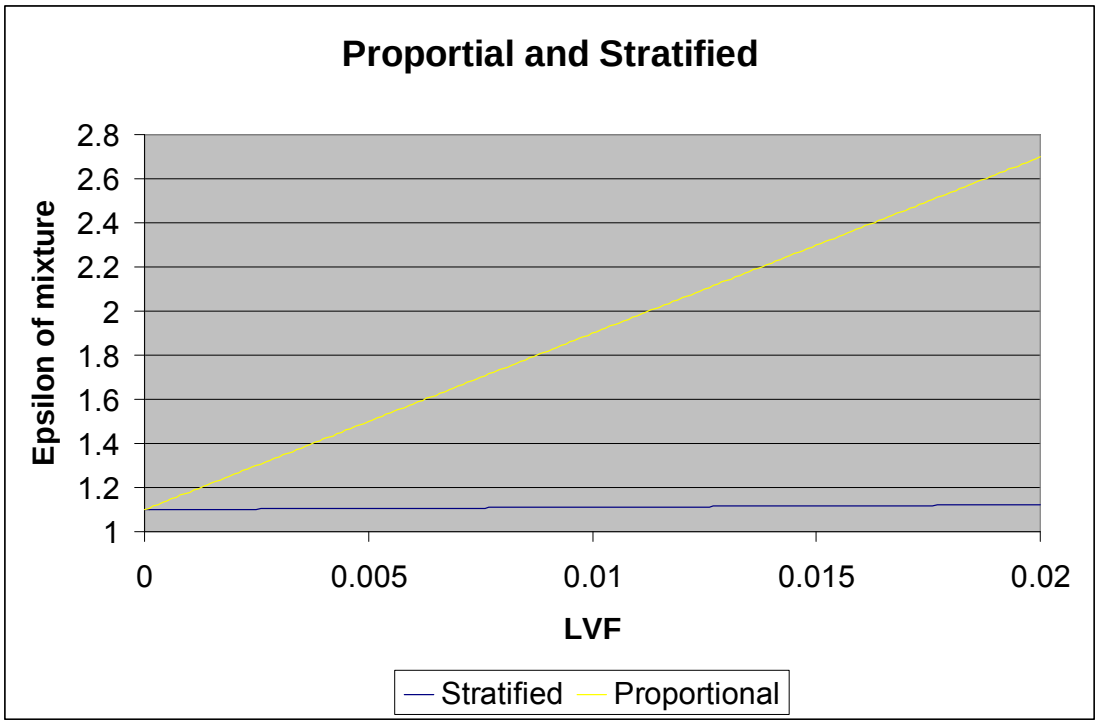

Figure 7: The difference in the estimated ε_m when the proportinal and stratified models are used in gas with water as liquid.

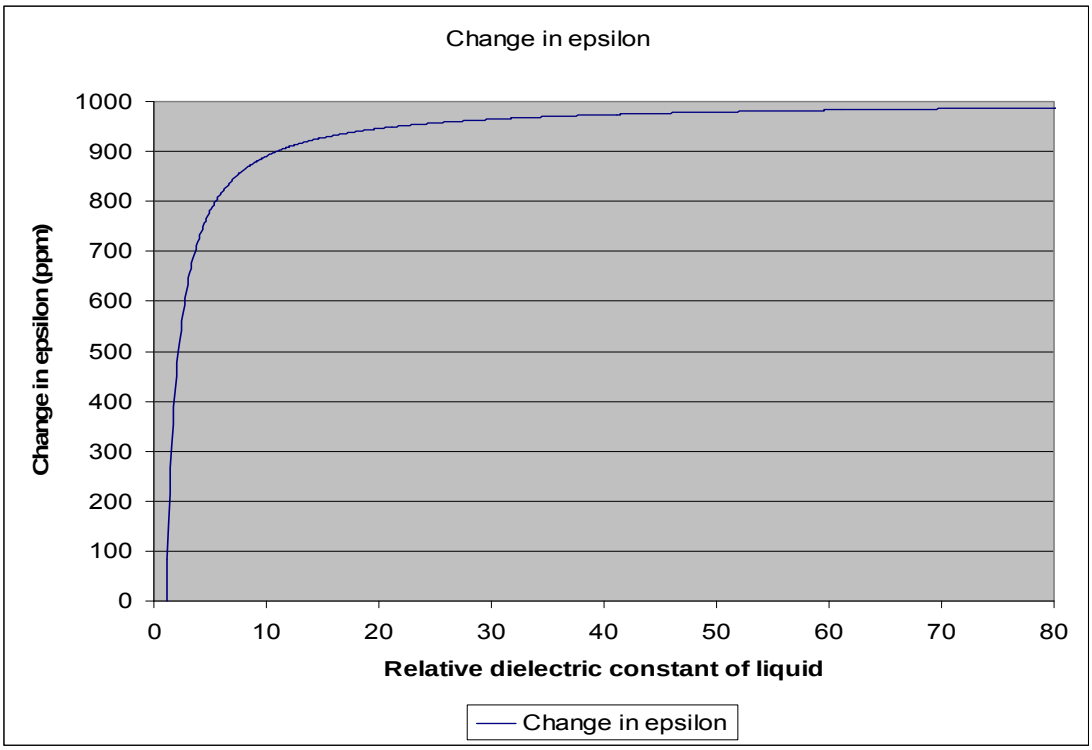

Figure 8: The influence of the capacitance of 0.1 v% of liquid as a thin layer at one of the plates as a function of the relative dielectric constant of the liquid with ε_g = 1.1. Note the rapid saturation (compare with fig. 7).

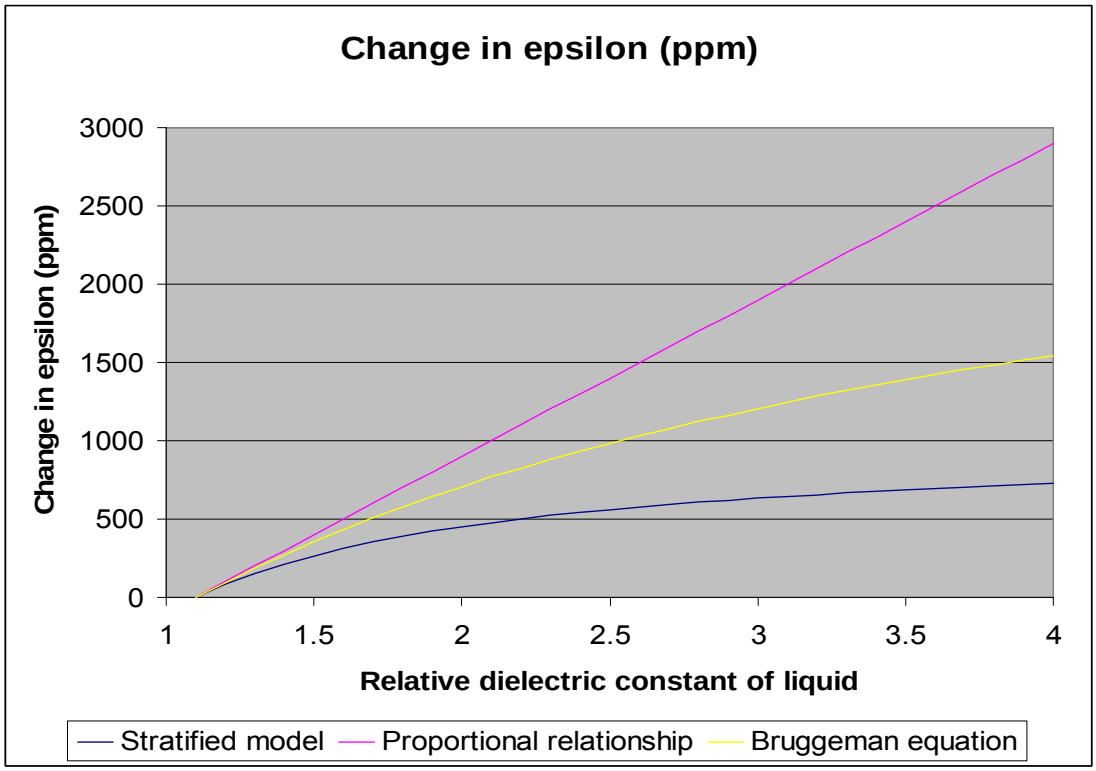

Figure 9: The changes of the relative dielectric constants as predicted by the Bruggeman model and the statified model. For reference, the proportional relationship is also shown. LVF = 0.1%, ε_g = 1.1.

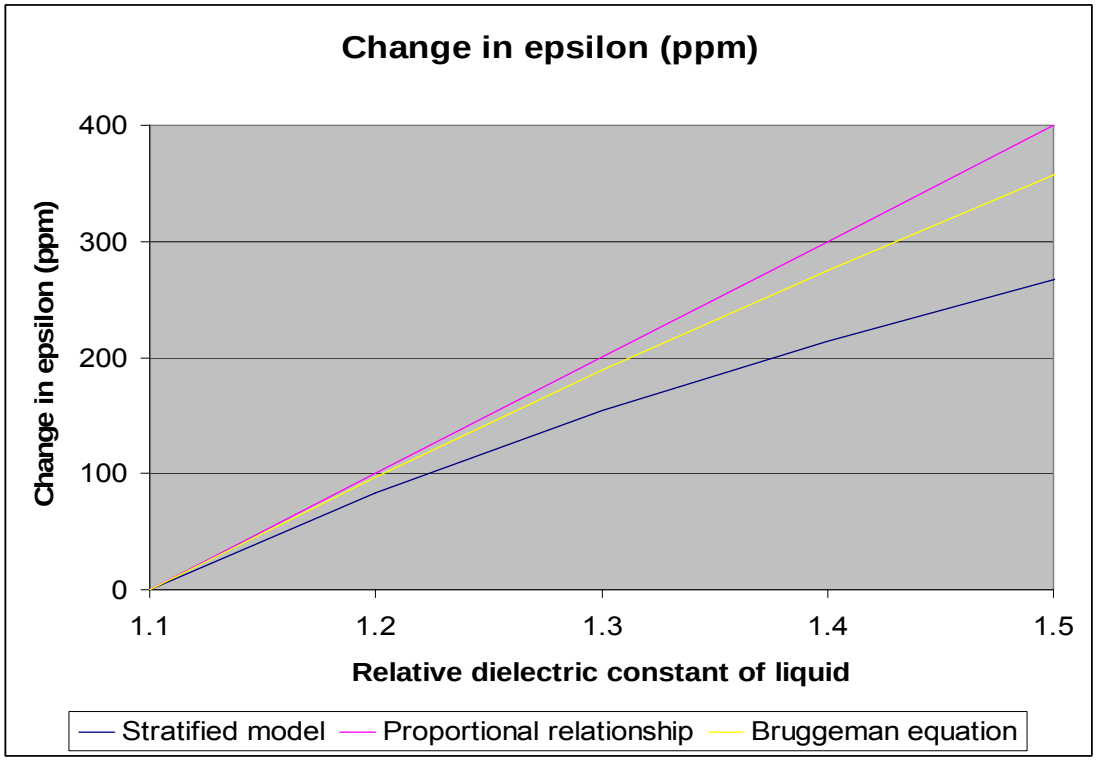

Figure 10: Enlargement of the changes of the relative dielectric constants as predicted by the Bruggeman model and the statified model. For reference, the proportional relationship is also shown. LVF = 0.1%, ε_g = 1.1. Note that for small values of ε_l the change is proportional to the relative dielectric constant of the liquid.

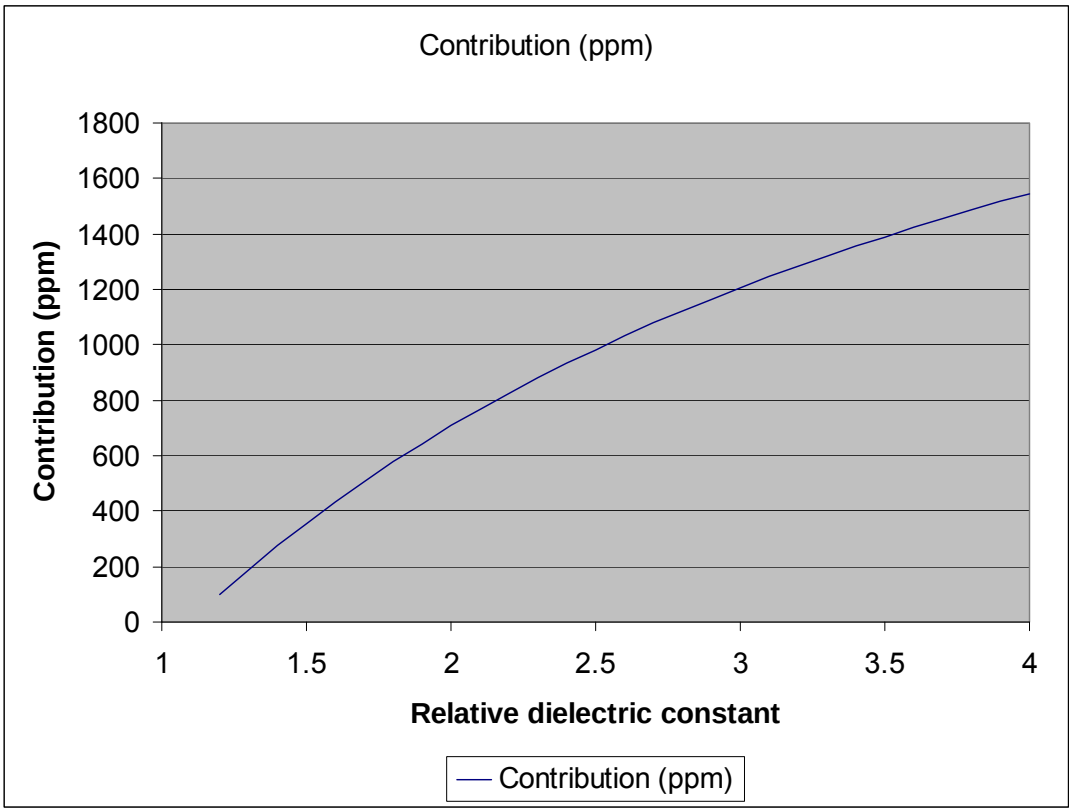

Figure 11: The contribution to ε_r for a fixed LVF of 0.1% as a function of the relative dielectric constant of the liquid using the Bruggeman model. The ε_r of the gas is 1.1

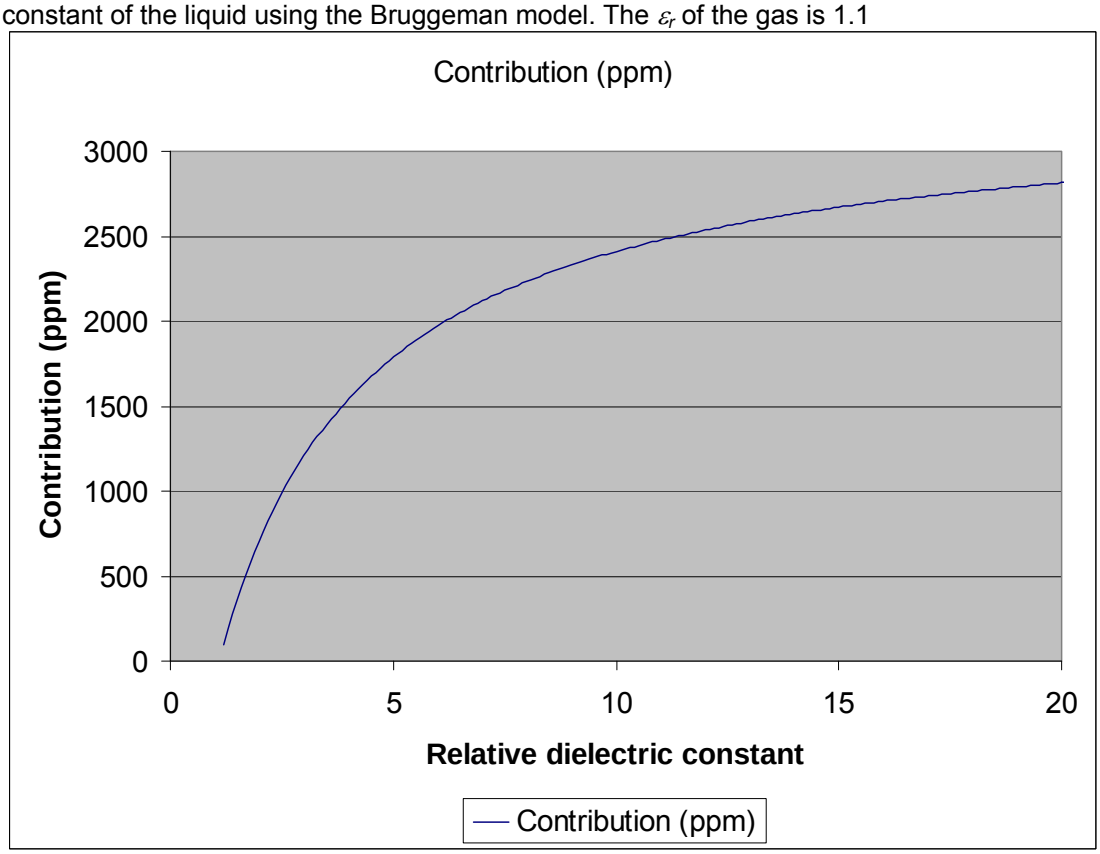

Figure 12: The contribution to ε_r for a fixed LVF of 0.1% as a function of the relative dielectric constant of the liquid using the Bruggeman model. The ε_r of the gas is 1.1. Note the deviations from a linear response of the effect.

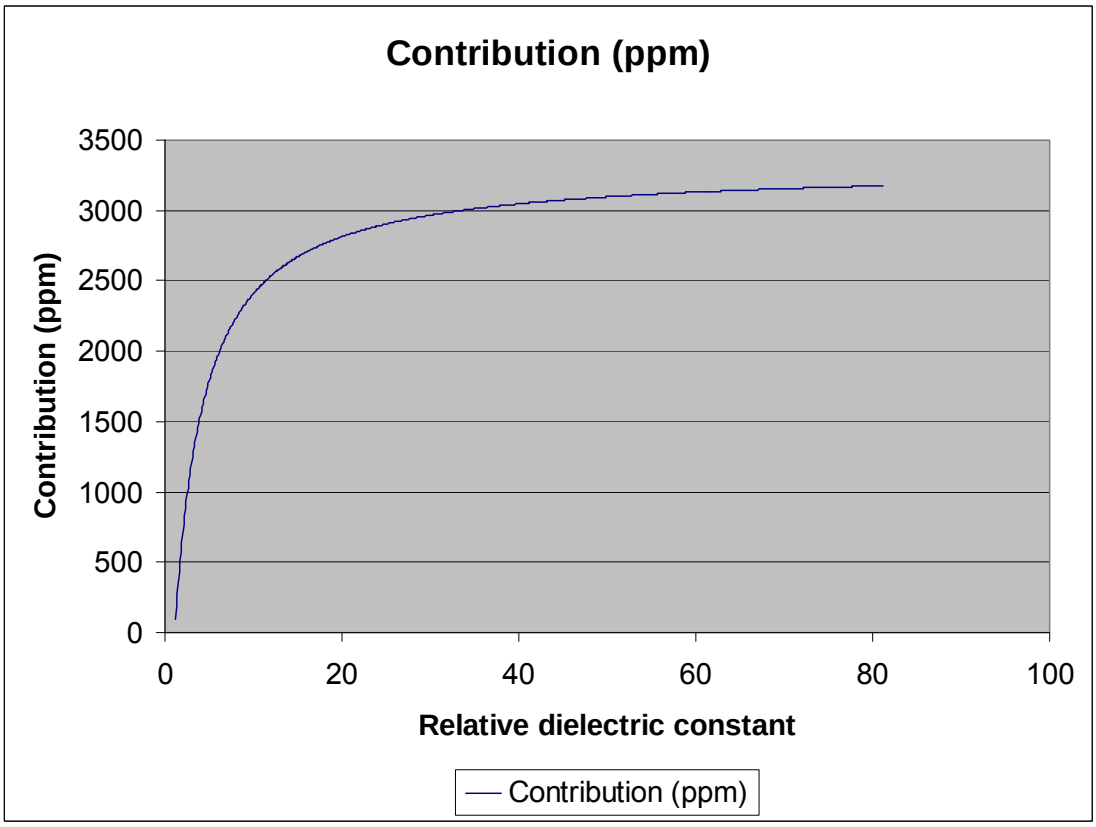

Figure 13: The contribution to ε_r for a fixed LVF of 0.1% as a function of the relative dielectric constant of the liquid using the Bruggeman model. The ε_r of the gas is 1.1. Note the saturation of the effect.

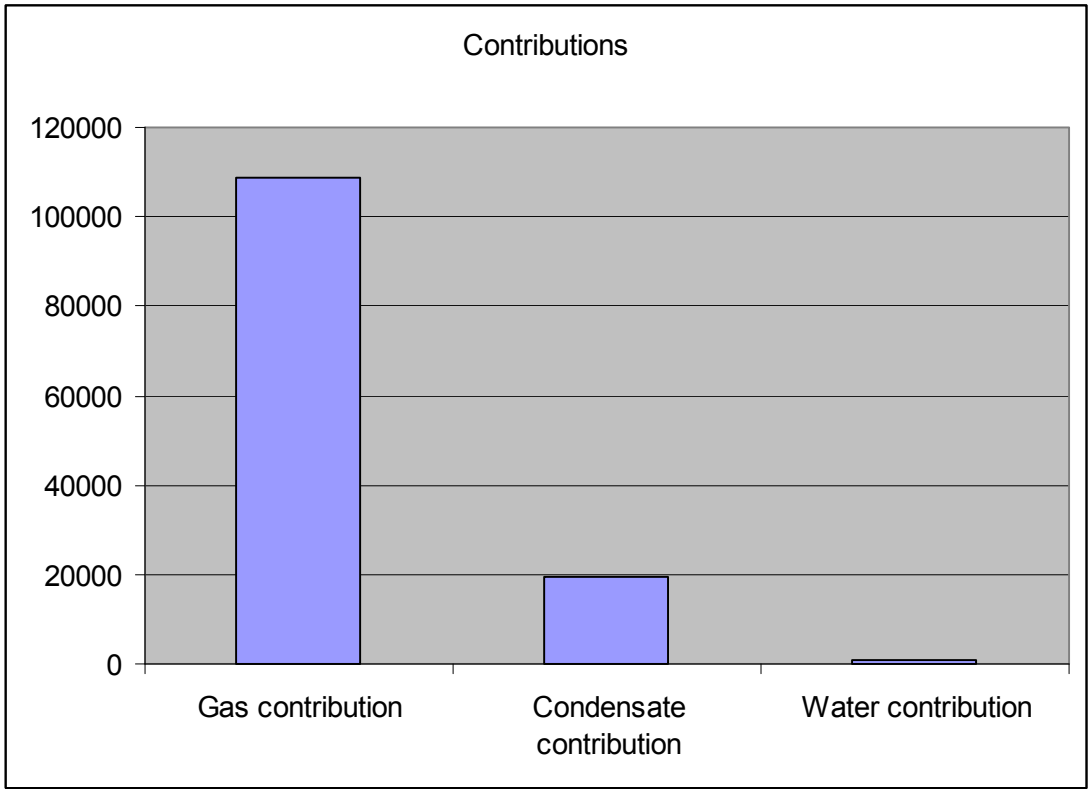

Figure 14: The contribution of the gas, condensate and liquid water to the ε_r of the mixture. (expressed as 10^6 . (ε_r - 1))

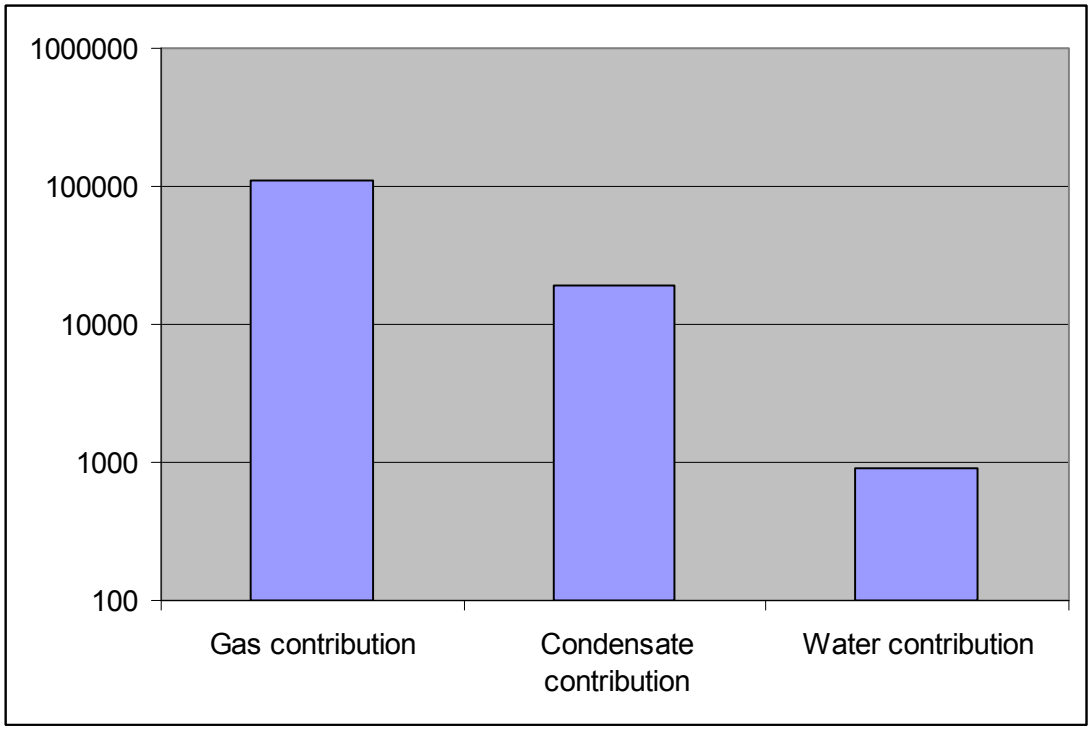

Figure 15: The contribution of the gas, condensate and liquid water to the ε_r of the mixture. (expressed as 10^6 . (ε_r - 1)). Note the logarithmic scale on the vertical axis.