36th International North Sea Flow Measurement Workshop
22-24 October 2018

Extensive analysis of performance of using Venturi meters for wet-gas conditions in field conditions.

D^r B. Pinguet TUV-SUD NEL

1. ABSTRACT

Venturi tubes are one of the most common type of devices used worldwide for wet-gas flow measurements as they are a simple, well-established technology, robust, and cost-effective flowmeters. They also form the main component in most of the commercial multiphase flow meters.

A large research effort has been spent over the past 60 years to develop robust correlations for the use of Venturi meters to correct the over-reading due to the unexpected presence of liquid in the gas phase; this led to the writing of the ISO/TR 11583 published in 2012. The uncertainty quoted for using this correlation is claimed to be between ±2.5% to ±3% and was based on extremely low uncertainties on the required input parameters, in other word the correlation was developed using data from flow laboratories with well characterised fluids. However, in the field conditions, the input parameter uncertainties which contribute to overall gas and liquid flowrate measurements could be substantially higher.

We proposed to establish the propagation of uncertainty when using Venturi meters for wet-gas flows and look at the true performance based on the uncertainty of all input parameters. It should be noted that when reviewing marketing information on the performance of multiphase and wet-gas flow meters, the uncertainties quoted are often from testing in flow measurement facilities with well-defined fluid properties and they are always at line conditions or without any additional fluid properties uncertainties, however, in the field the uncertainties from the meters can be substantially different and much higher.

The purpose of this paper is to highlight that applying corrections to compensate for well-defined over/under-readings, then the uncertainty of the input parameters must be considered to state the true performance. This is often overlooked. Furthermore, the uncertainty from the correlation equations are used as the total uncertainty on the meter performance but this over-simplifies and overlooks other major uncertainty contributions and can result in large measurement discrepancies. This can critically affect allocation and lead to potential disputes between production platforms or custody transfer.

Many installations in Asia Pacific, and the North Sea are using such wet gas equipment and for mitigating some of the uncertainty the use of additional measurements, such as tracers, to determine the liquid flow rate is used. In some cases, this measurement is only performed once a year and will still lead to high uncertainty in the determination of the liquid flow rate. A continuous measurement should be at the core of the strategy to handle wet gas flows.

This paper will provide practical information and recommendations that will enable more robust and accurate use of correlations applied to flowmeter based on differential pressure. This will ultimately assist in determining realistic uncertainty budgets and help all parties involved with assessing meters' performances and applications for allocation, etc. The propagation of error will be made up to the oil/condensate, water, and gas flow rate measurements.

1. INTRODUCTION

Over the last 160 years, the multiphase flow meter was the separator, and it is still the most common instrument used for looking the well by well performance. The main issues stated over the years and sometime forgotten by the end-user is that the technology is based on gravity separation, this means a significant density contrast between the phases is required to be able to separate them in a reasonable time (above 3-5 minutes).
The horizontal or smart wells development have been becoming more popular with multiple downhole sections and they have led to much larger productivity in the meantime the constraint with separators displacements on road have not changed keeping the similar overall dimensions. Then the retention time is becoming smaller for the fluid inside the separator and leading to issue about the quality of the separated phases flowing out of the separator (i.e. monophasic or not).
Very seldom service companies will provide two stage separations (i.e. two separators in series) to ensure a good separation between gas and liquid, and then between oil and water. Numerous studies have shown that a gas wetness of few percent can lead to a significant overestimation of single-phase metering device (i.e. 0.5% of liquid loading in gas line may lead to +2 to +8% overreading of gas flowrate versus line pressure). This could lead to wrong evaluation of the GOR or CGR and wrong statements about the reservoir conditions including wrong information as an input to retune a reservoir model. Furthermore, due to deeper well and equipment capable to handle higher pressure, the density contrast between the different phases has been significantly reduced. A lot of new devices have been added inside the separator to help the separation like coalescer for the liquid, demister for gas, or spinning process (cyclone) for the fluid to improve separation.
As stated by few oil and gas companies, getting better than ±5%-10% uncertainty for each phase require a fair involvement of expertise, instrumentation, and maintenance which is not always achievable with the cost of such field operation and the trend to reduce always the OPEX over the years. This raises some main questions: Is the oil industry happy with such uncertainty? Is it what the market need? Do we need to address the problem in different manners?

2. Approach of the Wet Gas Metering with Differential Pressure Devices

Starting in mid-80s, the wish to use a new way to address the well performance was initiated with the objective to have a flow metering solution per new well, the multiphase flow business started commercially some years later around mid-90s, the first 10 years of research and development led to solution that were sometime unrealistic to be used in the field (size, weight, cost, fragile…) or having technology or interpretation closer to the voodoo than scientific approach. This legacy about unrealistic statement or vision of multiphase and black box from the end of the 90's is still present today. Difficult to forget the investment in some cases in a business where wells can be flowing for 20 to 40 years. Early adopters in use of technology were burnt and the laggards less keen to use them.

1. Overreading in Wet Gas Business

Mid-2000's has seen a new commercial business approach in with the Wet Gas which is a subset of Multiphase Flow but for gassy conditions (GVF > ~90%) or gas wells. The work started way earlier in the nuclear domain with steam and water and then based on a solid 60 years development or experiences. Some manufacturers started to use such expertise in this simpler flow regimes conditions (figure 1) highlighted in blue are the typical flow regimes representing the high GVF. Multiple statements or definition exist about what is a WET GAS, and, in a way, this shows the little convergence in this business around some simple concepts. This is sometime driven more by manufacturers (marketing or sales pitch) than science and generic definition.

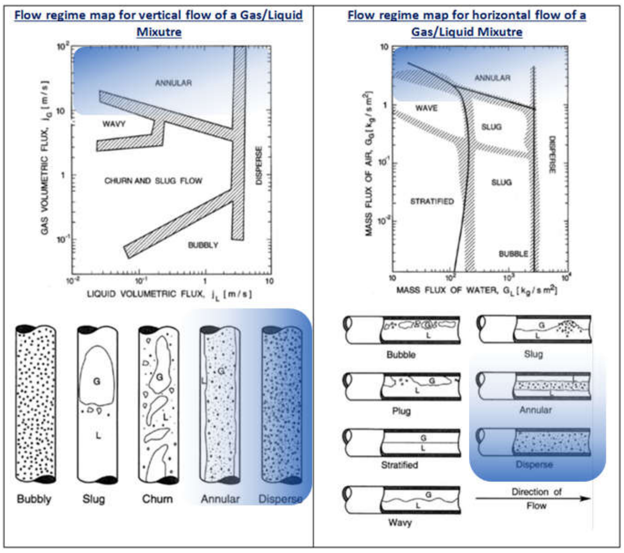

Figure 1: Highlighted in blue the most common flow regime in Wet gas

Meanwhile, the core of the research on the wet gas meter with differential pressure design (i.e Venturi, Orifice Plate) over 60 years has shown that the typical use of the equation of the ISO 5167 assuming only gas presence leads to large overreading of the gas flowrate if the mixture density is not corrected of the presence of the liquid. To address this problem of overreading without changing the initial gas density in the use of the ISO 5167, a correction of the liquid loading or Lockhart-Martinelli parameter (figure 2) was introduced.

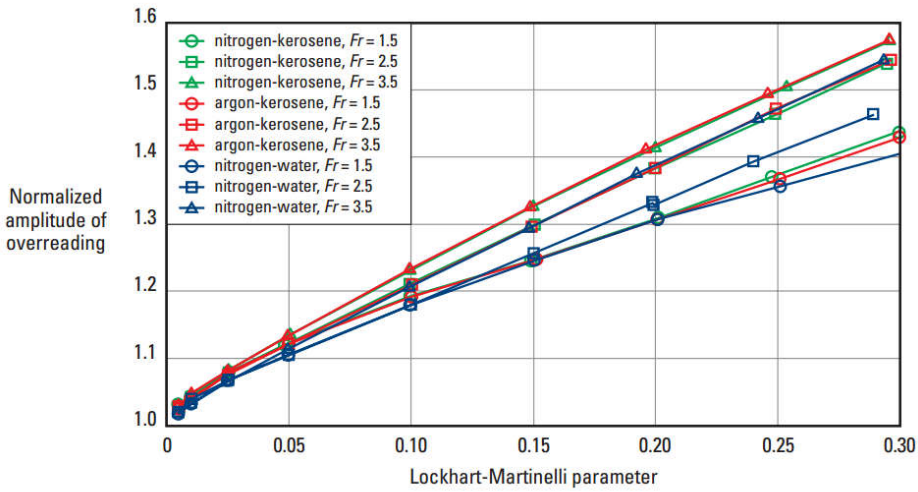

Figure 2: Venturi overreading of the gas rate versus liquid loading [2]

2. Differential Pressure Measurement and Overreading Correction

The mass flow rate as defined by ISO 5167 can be expressed by:

$$q_m = C\sqrt{\frac{2}{1-\beta^4}}\varepsilon\frac{\pi}{4}d^2\sqrt{\Delta P.\rho_m} \tag{1}$$

C is the discharge coefficient, d is the throat diameter,
ρ is the density of the fluid at the Venturi throat?
ε is the expansibility factor

As a reminder the ISO 5167 is also indicating the range of conditions where C for example is defined or if the meter should be flow calibrated or not (i.e. establish the C value).

Common in the oil and gas industry is the presence of some condensate (in vapor or liquid phase following the pressure and temperature), or steam (vapor of water for high temperature well which has always a bit of water), or d carryover inside a separator (retention time too short, or/and demister not working properly). As early as the 60's, it was noted that the use of non-dry gas was leading for orifice plate to a significant overreading. Extensive works were made to provide a correction on this overreading, the work of Murdock (1962) on orifice plate with the following equations could be set as a first main milestone:

$$q_{gas} = \frac{q_{gas\_tp}}{\phi} = \frac{C}{\phi}\sqrt{\frac{2}{1-\beta^4}}\varepsilon\frac{\pi}{4}d^2\sqrt{\Delta P.\rho_g} \tag{2}$$

It is important to understand that the density at the throat of the Venturi was kept as being only the gas phase and then doing a mathematical correction. It was expected to be a small contamination and the expression for the correction was:

$$\Phi = 1 + 1.26X \tag{3}$$

X defining the Lockhart-Martinelli Parameter in this document, and defined by:

$$X = \frac{q_{m\_liq}}{q_{m\_gas}}\sqrt{\frac{\rho_g}{\rho_l}} = \frac{(1-GVF)}{GVF}\sqrt{\frac{\rho_l}{\rho_g}} \tag{4}$$

with $GVF = \dfrac{Q_g}{Q_g + Q_l}$ (5)

3. Slip Law Equation Hidden inside the Correction Factor

It is interesting to combine the equations above (1) and (2) and to find that the overreading correction is linked to the GVF:

$$\frac{1}{\phi} = GVF.\sqrt{\frac{\rho_g}{\rho_m}} \tag{6}$$

The issue with this equation is, a priori, we have access to only one information which is the gas density at the throat of the Venturi, then it is necessary to evaluate mixture density which required to know the wetness and then the slippage or the gas volume fraction. If we could imagine getting access to the density by adding a density meter for example, there is no way to get GVF measurement directly.
Put back in perspective the work done by most of the inventors from this date will be, only, to identify some key parameters and then model the above equation.

Assuming the expression of the overreading is the following formulation (7) which is discussed later about the validity, C_n (sometimes refers by C_{ch} for the initial work of Chisholm but it is making more sense in this document, at least, to highlight the entire vision and being not restrictive to a specific differential pressure equipment) is representing the multiple correlations developed over the years and more specifically we will see the formulation of the estimator "n"

$$\phi = \sqrt{1 + C_n.X + X^2} \tag{7}$$

Before going further, using (4), (6) and (7), it is possible to establish a slip law for wet gas by solving the following quadratic equation:

$$\left(\sqrt{\frac{\rho_g}{\rho_l}}+\sqrt{\frac{\rho_l}{\rho_g}}-C_n\right) GVF^2+\left(C_n-2\sqrt{\frac{\rho_l}{\rho_g}}\right) GVF+\sqrt{\frac{\rho_l}{\rho_g}}-\frac{1}{\sqrt{\frac{\rho_l}{\rho_g}\frac{\rho_g}{\rho_m}}}=B_0 GVF^2+G_0.GVF+P_0=0 \quad (8)$$

And knowing that GVF must be ≤1, we obtain:

$$GVF=\frac{-G_0}{2B_0}\left(1-\sqrt{1-4.\frac{B_0 P_0}{G_0{}^2}}\right)=B_1\left(1-\sqrt{1-4.P_1}\right) \quad (9)$$

With $B_1=-\frac{1}{2}\left(C_n-2\sqrt{\frac{\rho_l}{\rho_g}}\right)$ and $P_1=\frac{\left(1-C_n\sqrt{\frac{\rho_l}{\rho_g}}+\frac{\rho_l}{\rho_g}\right)\left(1-\frac{\rho_m}{\rho_l}\right)}{\left(C_n-2\sqrt{\frac{\rho_l}{\rho_g}}\right)^2}$

This is an interesting expression because this estimation of the GVF requires only the liquid, gas, and mixture density, and indirectly the slip is obtained without any other tuning factor than only one parameter which is "n" and it was reviewed and estimated over the last 60 years by all the inventors. In very high GVF (i.e. >98%), the expression given above follow the linear behaviour as highlighted by some previous publication. It will be interesting to verify this expression (9) and challenge it for the high GVF. Here below is presented the Gas Volume Fraction (in blue) versus Gas Fraction (Y-axis on the left), and in red is presented on the right Y-axis the difference between both variables. Both curves are presented versus the gas fraction, which is a parameter easily measurable. The expression (9) should not be correctly represented the slippage when the liquid loading is very high which is related to the modelling of n and its domain of application.

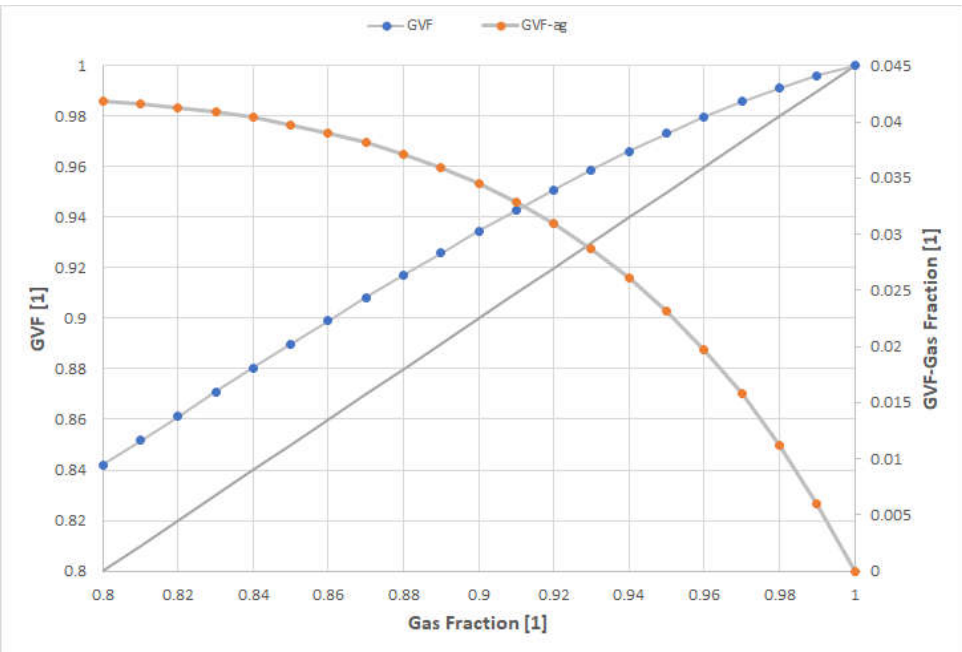

Figure 3: Evaluation of the Gas Volume Fraction versus Gas Fraction with the Cn calculated from the ISO 11583 with Fr_g=3 and a β =0.4.

4. Main steps in the development of the Overreading Correction Factor

Murdock [7] had initially thru a limited set of data (<100 datapoints) established the equation here below (10) for orifices in 1962. It was reported that the correlation was valid from 10 to 63 bara, β from 0.2 to 0.5, Venturi size from 2.5 to 4in, and X < 0.25. The fluid properties were Gas/hydrocarbons, Gas/Salt water, air/water, wet steam.

$$\phi = 1 + M \cdot X = 1 + 1.26X \qquad (10)$$

The work of Chisholm [6] for orifice plate (NEL in 1967) and keeping a structure identical to Murdock was valid for line pressure <70 bara, and X <0.3. It was indicted in his work that following the line pressure the coefficient M needed to be changed, and based on the development of a solution for homogenous conditions proposed the following expression:

$$\phi = \sqrt{1 + C_{CH} X + X^2} \qquad (11)$$

and

$$C_{CH} = \left(\frac{\rho_{liquid,line}}{\rho_{gas,line}}\right)^n + \left(\frac{\rho_{gas,line}}{\rho_{liquid,line}}\right)^n \qquad (12)$$

with the value of n=0.25

It is interesting to show that X being a small quantity initially then by Taylor expansion of the equation (11), we converge to the same structure of equations than Murdock:

$$\Phi \sim 1 + \frac{C_{CH}}{2} X \qquad (13)$$

Furthermore, the structure of the Chisholm's coefficient can be understood by using simply doing the calculation for a homogenous flow.

$$Q_{tot} = Q_g + Q_l = \frac{q_m}{\rho_m} = \frac{q_g}{\rho_g} + \frac{q_l}{\rho_l} \qquad (14)$$

$$\text{and } \frac{1}{\rho_m} = \frac{1}{\rho_g}\frac{q_{gas}}{q_m} + \frac{1}{\rho_l}\frac{(q_m - q_{gas})}{q_m} = \frac{x}{\rho_g} + \frac{(1-x)}{\rho_l} \qquad (15)$$

By using the definition of the mass quality "*x*", we have $q_{gas} = x.q_m$ and we can rewrite the overreading ϕ (2) with

$$\phi = \frac{q_{gas\_tp}}{q_{gas}} = \frac{q_{gas\_tp}}{x \cdot q_m} = \frac{1}{x}\sqrt{\frac{\rho_g}{\rho_m}} = \frac{1}{x}\sqrt{\rho_g \frac{x}{\rho_g} + \rho_g \frac{1-x}{\rho_l}} = \frac{1}{x}\sqrt{\frac{\rho_g}{\rho_l} + x - x\frac{\rho_g}{\rho_l}} \qquad (16)$$

We have finally, by using the definition of the Lockhart-Martinelli parameter (4):

$$\frac{1}{x} = \frac{q_m}{q_{m\_gas}} = 1 - \frac{q_{m\_liq}}{q_{m\_gas}} = 1 + X\sqrt{\frac{\rho_l}{\rho g}} \qquad (17)$$

and

$$\phi = \sqrt{\frac{\rho_g}{\rho_l}\frac{1}{x^2} + \frac{1}{x} - \frac{1}{x}\frac{\rho_g}{\rho_l}} = \sqrt{1 + X\sqrt{\frac{\rho_l}{\rho_g}} + X\sqrt{\frac{\rho_g}{\rho_l}} + X^2} = \sqrt{1 + X \cdot (\sqrt{\frac{\rho_l}{\rho_g}} + \sqrt{\frac{\rho_g}{\rho_l}}) + X^2} \qquad (18)$$

We find the Chisholm structure (i.e. equation (11)) with this time n=0.5. The interest in this demonstration its to show that there are some physics and mathematics to explain how to build this overreading correction model. This is somewhere pleasing to see that it is built on some right basis and reinforce the effort made after this time.

Some works [8] were done after that, but the next main step was the work from de Leeuw, in 1997 [2], where working on different range of line pressures (i.e. 15, 30, 45, 90 bara) for a fix β (=0.401) and a 4in Venturi (d=39mm) on the SINTEF facility, it was highlighted on recording about 100 datapoints a deviation of the previous correlation and revisited the Chisholm correction by introducing a dependency versus the Froude number (in the initial study from 1.5 to 4.8, and the Lockhart-Martinelli was between 0 and 0.3, the GVF following the conditions from 90% to 100%). The correlation was claimed to work above 90 bara and it should not be used below 17kg/m3 (~15bara). This was extended later to Fr_g from 0.5 to 4.8, and X from 0 to 0.34. The structure of Chisholm correlation was kept but the n was expressed with the following expression introducing the Froude number dependency:

$$\begin{aligned} n &= 0.41 && with \quad Fr_g \in [0.5, 1.5[\\ n &= 0.606(1 - e^{-0.746.Fr_g}) && with \quad Fr_g \geq 1.5 \end{aligned} \tag{19}$$

The Froude number is, by definition, the square root of the ratio of the kinetic energy of a given phase to the generic gravitational potential energy. In simple terms, this is a number characterizing for liquid if the droplets will be carried by the gas flowrate or the relative gravity will bring them to the bottom of the pipe quickly. Higher is this number and then mistier will be the flow (droplets being carried), lower will be this number and more stratified will be the flow for 2 phases (liquid & gas) with accumulation of the liquid at the bottom of the pipe due to the gravity effect. The variation of “n is presented on the figure 4.

It should be noted that using the definition for the Froude number for liquid and gas it is related to the Lockhart-Martinelli.

$$X = \frac{q_{m\_liq}}{q_{m\_gas}}\sqrt{\frac{\rho_g}{\rho_l}} = \sqrt{\frac{q_{m\_liq}^2 / gD(\rho_l-\rho_g)}{q_{m\_gas}^2 / gD(\rho_l-\rho_g)}\frac{\rho_g}{\rho_l}} = \sqrt{\frac{\dfrac{q_{m\_liq}^2 / \rho_l.(\frac{\pi d^2}{4})^2}{gD(\rho_l-\rho_g)}}{\dfrac{q_{m\_gas}^2 / \rho_g.(\frac{\pi d^2}{4})^2}{gD(\rho_l-\rho_g)}}} = \sqrt{\frac{\dfrac{V_{\sup,liq}^2\rho_l}{gD(\rho_l-\rho_g)}}{\dfrac{V_{\sup,gas}^2\rho_g}{gD(\rho_l-\rho_g)}}} = \sqrt{\frac{Fr_l^2}{Fr_g^2}} = \frac{Fr_l}{Fr_g} \tag{20}$$

Stewart et al (Flow programme at NEL 1999-2002) [4] demonstrated in an exhaustive manner (Pressure: 15, 30, 60bara, Fr_g: 0.5 to 5.5, β: 0.4, 0.6, 0.75) the dependency of the established previous correlations versus β. A clear deviation was seen at high β (i.e. from 0.5 to 0.75) which was obviously not investigated before. It confirmed the findings about the dependency versus Froude number highlighted earlier.

This led around 2009 up to 2012 to an initiative to revisit the overreading and concluded by the writing of the International Standard (ISO 11583:2012) with a new evaluation of the “n” factor. The correction is now introducing another parameter after β which is based on the type of fluid and defined by H. This value has no unit and change from 1.35 to 1 with respectively 100% water and 100% oil, this H could be presented as a potential function of the surface tension of the liquid albeit it has not been explicated that way. From the analysis of some data the dependency is quite weak and improve the uncertainty by ~¼ of percent. Probably with a review of more data and some deeper analysis an improvement will be happening over the next years. It is the view of the author that correlations should be as much as possible using the generic similitude parameters defined in the literature and this should be addressed here by maybe a weber number. The new calculation of “n” as presented inside the ISO 11583 is:

$$n = \max(0.583 - 0.18\beta^2 - 0.57e^{-0.8\frac{Fr_{gas}}{H_{mix}}}, 0.392 - 0.18\beta^2) \tag{21}$$

$$H_{mix} = H_{water}WLR + H_{hydrocarbon}(1 - WLR) \tag{22}$$

With for domain of application $\beta \in [0.4, 0.75]$ $D \geq 50mm$ $Fr_g > 3\beta^{2.5}$ $\frac{\rho_g}{\rho_l} > 0.02$ $X \in]0, 0.3]$

The ISO 11583 was estimated to have been tested over more than 4,000 datapoints by third calibration facility, and more than 2,500 have been traceable at this date with different gas (Natural Gas, Argon, Nitrogen, steam) and different liquids (Water, Decan, Refined Oil, Very, Hot Water, Solvent…) and different Venturi sizes and diameter ratio (0.4 to 0.75). Later it is indicated that this was extended way beyond this initial statement [8].

The interest of the ISO11583 is to generalize the overreading solution not only for Venturi but also for Orifice plate like the ISO 5167. The evaluation of “n” is given hereafter for Orifice plate:

$$n = 0.214 \quad with \quad Fr_g \in [0.2, 1.5[$$

$$n = \left(\frac{1}{\sqrt{2}} - \frac{0.3}{\sqrt{Fr_g}}\right)^2 \quad with \quad Fr_g \geq 1.5 \tag{23}$$

with $\beta \in [0.24, 0.73]$ $Fr_g > 0.2$ $X \in]0, 0.3]$ $D \geq 50mm$ $\frac{\rho_g}{\rho_l} > 0.014$

5. Evolution of the correlations used for the Overreading Correction Factor

The figure 4 is showing the evaluation of the ‘n” factor for the different correlations. The curves follow a same trend following if it was developed for orifice or for Venturi except at lower Froude number (<1.5 for the Venturi). We are not trying to justify the difference because they are not strictly comparable (see chapter 6) and the overall overreading should be the relevant comparison to do. The message is a large effort over the last 60 years was spent on tuning an equation and by adding few variables improving step by step the correction and this should be granted but, form the author point of view, without necessary adding a significant effort on the physics understanding.

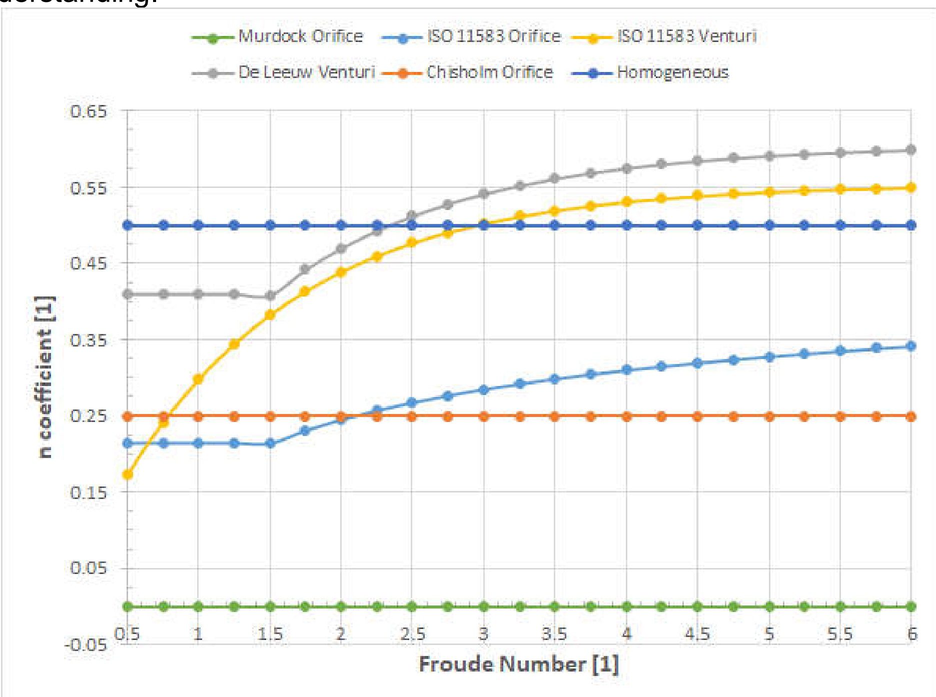

Figure 4: the “n” coefficient evaluation for the main correlations used in Wet Gas Flow and a β =0.4.

6. Review of the different overreading correction factors

It is very interesting, from the author point of view, for the first time to see the introduction of a specific correction on the discharge coefficient “C” (see equation (2)). There is from a physics point of view no reason that C should be equivalent to the dry discharge coefficient knowing that some liquid will be wetting the wall and then the roughness will not be anymore the same for the least. This is an effort to highlight. The revisiting of “C” versus β factor and Froude number led to the following expression:

$$C = 1 - 0.0463 \cdot e^{-0.05\frac{Fr_{gas}}{\beta^{2.5}}} \min(1, \sqrt{\frac{X}{0.016}}) \tag{24}$$

with $\beta \in [0.4, 0.75]$ $D \geq 50mm$, $Fr_g > 3\beta^{2.5}$ $\frac{\rho_g}{\rho_l} > 0.02$, $X \in]0, 0.3]$

The discharge coefficient is used to compensate for the friction of the fluid against the wall. In a generic way between the two pressure holes at the Venturi inlet and the throat. The Venturi equation should have been written the way presented below (25) from a scientific point of view, and a correction directly on the DP reading should be applied. From an engineering point of view, it was simpler to implement a correction upfront leading to:

$$q_m \sim \sqrt{\frac{2}{1-\beta^4}}\varepsilon\frac{\pi}{4}d^2\sqrt{\Delta P_{Velocity}.\rho} = \sqrt{\frac{2}{1-\beta^4}}\varepsilon\frac{\pi}{4}d^2\sqrt{(\Delta P_{Reading} - \Delta P_{Friction}).\rho} \tag{25}$$

Let’s develop slightly more this equation and we get:

$$C^2.\Delta P_{Reading} \sim \Delta P_{Velocity} = (\Delta P_{Reading} - \Delta P_{Friction}) \tag{26}$$

or $$C \sim \sqrt{1 - \frac{\Delta P_{Friction}}{\Delta P_{Reading}}} \tag{27}$$

This shows clearly that large frictions (i.e. viscous fluids) requires correction on the C value, and uncertainty on low ΔP reading will introduce some additional error. This is common sense, but it was worth to mention it. In the wet gas conditions, the liquid wet the wall and then the surface roughness will change and then the friction from dry gas conditions.

If the dependency versus Froude number seems relevant from a scientific point of view because it is addressing in a way the quality of the mist, unfortunately the structure of the equation is not explained but it will be shown it is working very well and beyond the initial work of the inventors. The dependency versus Lockhart-Martinelli which means the ratio of liquid and gas density and the quantity of liquid flowing thru the pipe is relevant. It is also important to keep in mind that the flow of 2 or 3 phases is going thru a large “stress” between the upstream pressure port at the Venturi and the throat one. The velocity is increasing significantly when in the same time the pressure is coming down leading to an expansion of the gas, moreover the concentric design leads also to have liquid on the venturi convergent to flow to the centre of the pipe at the inlet of throat when in the same time a large concentration of gas at large velocity is present in the core annulus. The Venturi, in such flow conditions, could be seen like an injector, generating droplets of smaller size which will lead to energy lost and this is associated with the size and then the superficial tension. This H can explain quantitatively why the concept of superficial tension as introduced indirectly should be a relevant parameter to use, probably a similitude number like Euler, or Weber number will be more adequate.
In figure 5 is presented the overreading for the different correlations for a Froude number=1 and a gas density ~30kg/m^3 and liquid density ~800kg/m^3, the trend is the same for all correlations versus X, there are little differences between the Murdock and Chisholm, the homogenous flow is way overestimating the correction. It should be noted that the discharge coefficient correction

for ISO 11583 is included the overreading correction and then a strict comparison can be done among all of them.
Most of these correlations and for the latest ones are clipped at a Lockhart Martinelli <0.3, but the author has seen some uses beyond this value and up to 0.5. It does not mean this was developed on this extended range or it is valid, but the behaviour wanted to be shown.

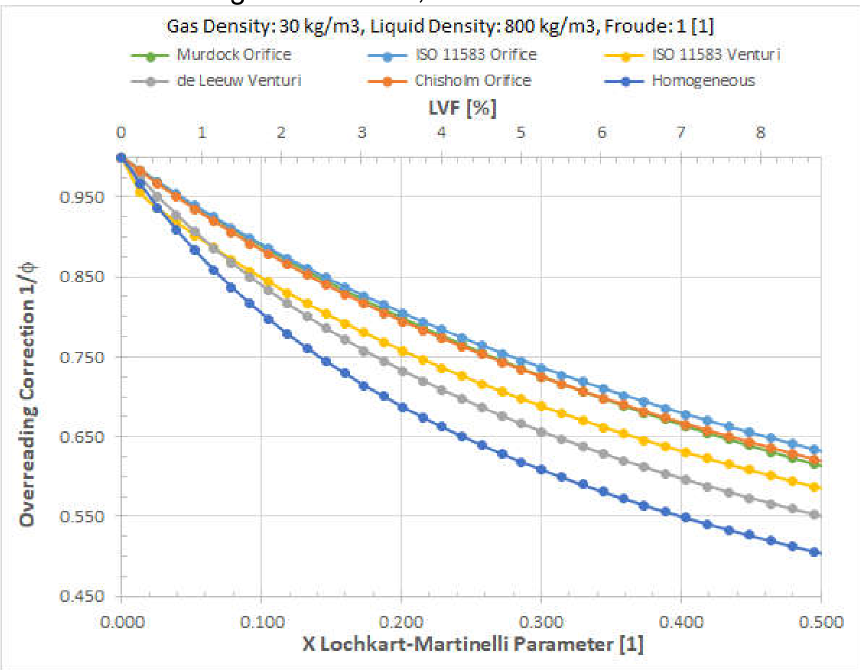

Figure 5: Overreading correction factor against the Venturi equation with a gas density ~30kg/m3; liquid density ~800kg/m3, β=0.4, and a Froude number=1, LVF [%] = 100-GVF [%] is presented on the upper x-axis. LVF is pressure dependent and X versus LVF needs to be recalculated for each line pressure

The normalization of the data presented on the figure 5 was done against the ISO 11583 for either Venturi or Orifice plate. It can be seen clearly that the deviation of the Murdock and Chisholm versus ISO Orifice is in the order of couple of percent at X=0.3. The deviation is larger for the Venturi design.

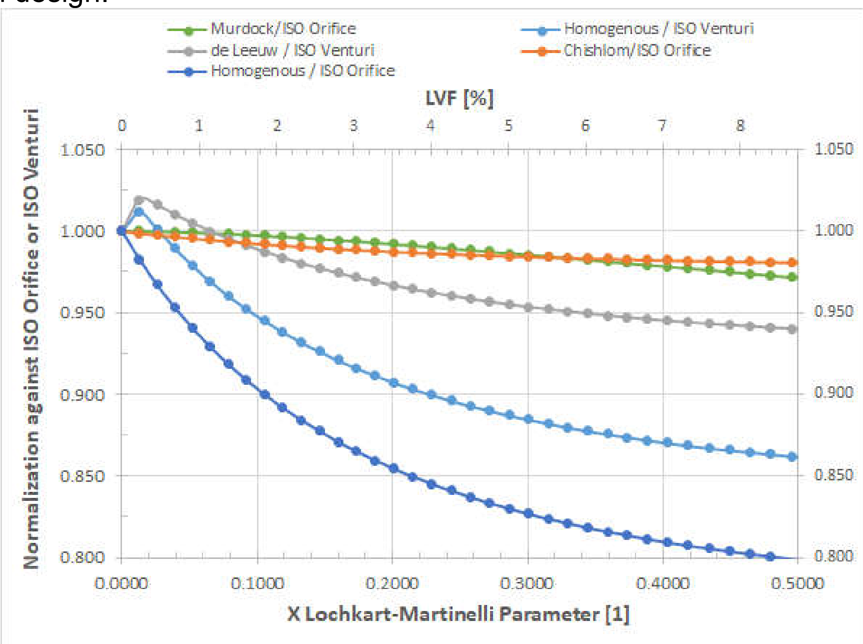

Figure 6: Normalization of the correlation against the ISO 11583 Venturi or Orifice with a gas density 30kg/m3; liquid 800kg/m3, β=0.4 and a Froude number=1, the LVF [%] =100-GVF [%] is presented on the upper X-axis.

The same type of presentation than above is presented on the figures 7 & 8 but for a higher gas density ~ 60 kg/m3 everything else being equal. It can be noted that the correction for the orifice and Venturi seem to start collapsing to common solution. All correlations from the past are within ±2.5% (worst case X=0.3) now against the ISO 11583.

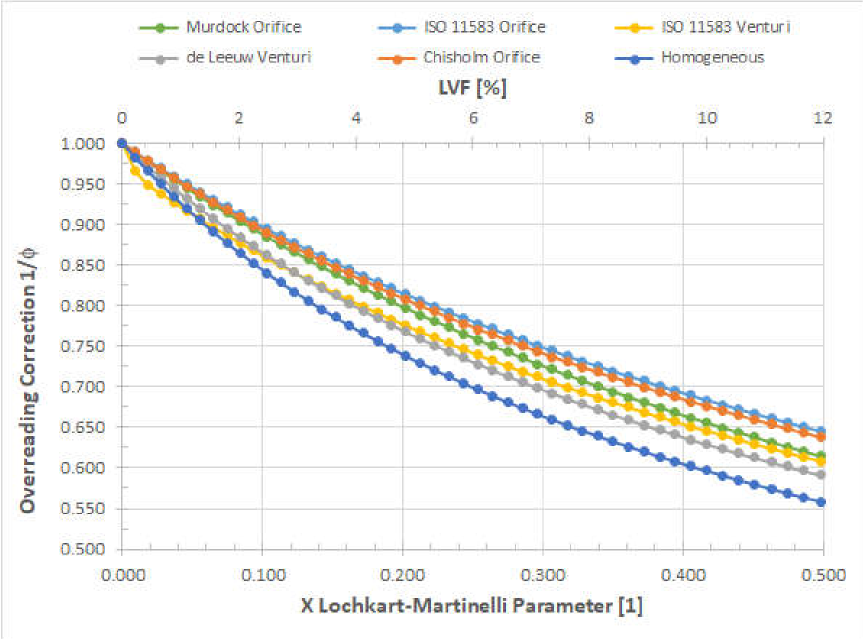

Figure 7: Overreading correction factor against the Venturi equation with a gas density 60kg/m3; liquid 800kg/m3, β=0.4 and a Froude number=1, the LVF [%] is presented on the upper x-axis.

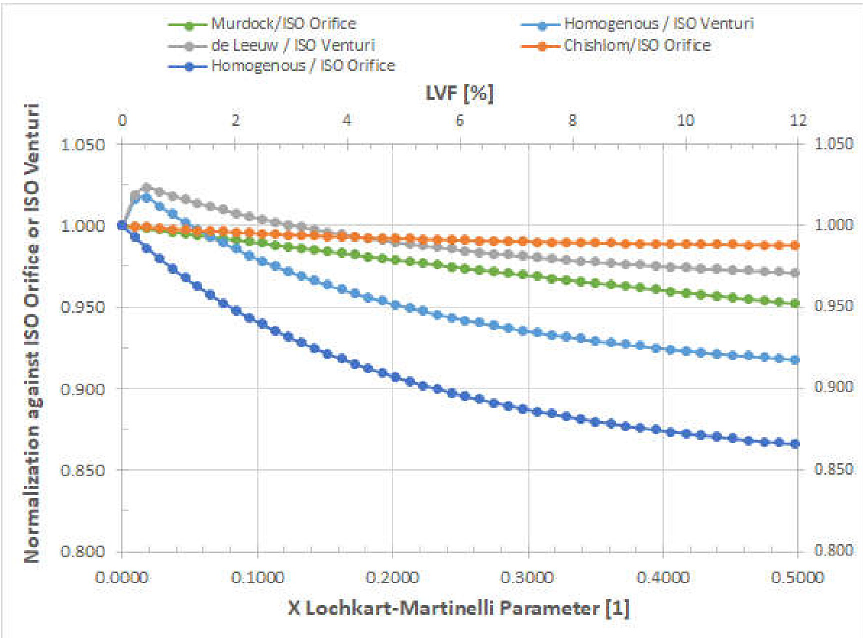

Figure 8: Normalization of the correlation against the ISO 11583 Venturi or Orifice with a gas density 60kg/m3; liquid 800kg/m3, β=0.4 and a Froude number=1, the LVF [%] is presented on the upper x-axis.

It should be noted than the loading in terms of LVF (upper X-axis) is much higher now for the comparison to the Lockhart-Martinelli parameter due to the pressure change.

The same type of figures than above is presented now for gas density ~ 120 kg/m3 and everything else being equal.

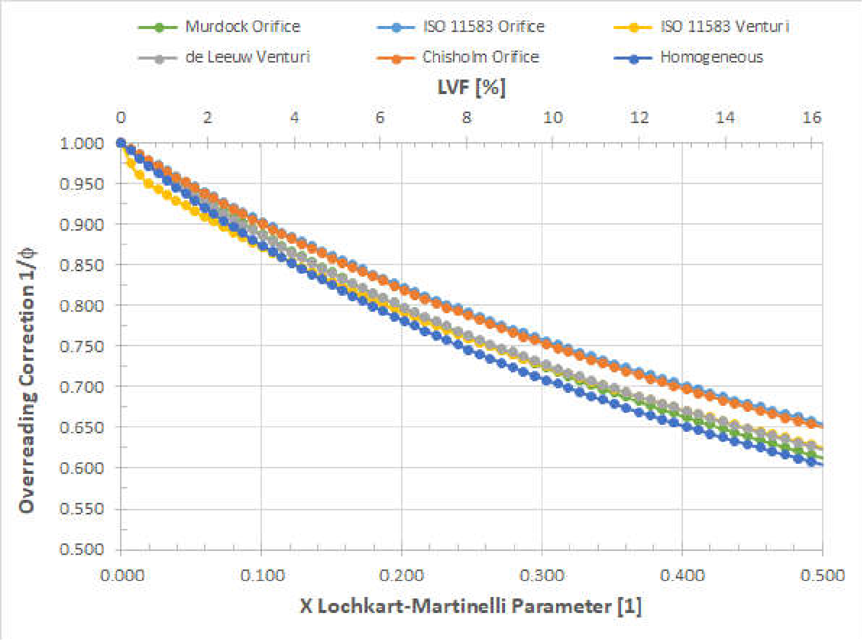

Figure 9: Overreading correction factor against the Venturi equation with a gas density 120kg/m3; liquid 800kg/m3, β=0.4 and a Froude number=1, the LVF [%] =100-GVF [%] is presented on the upper x-axis.

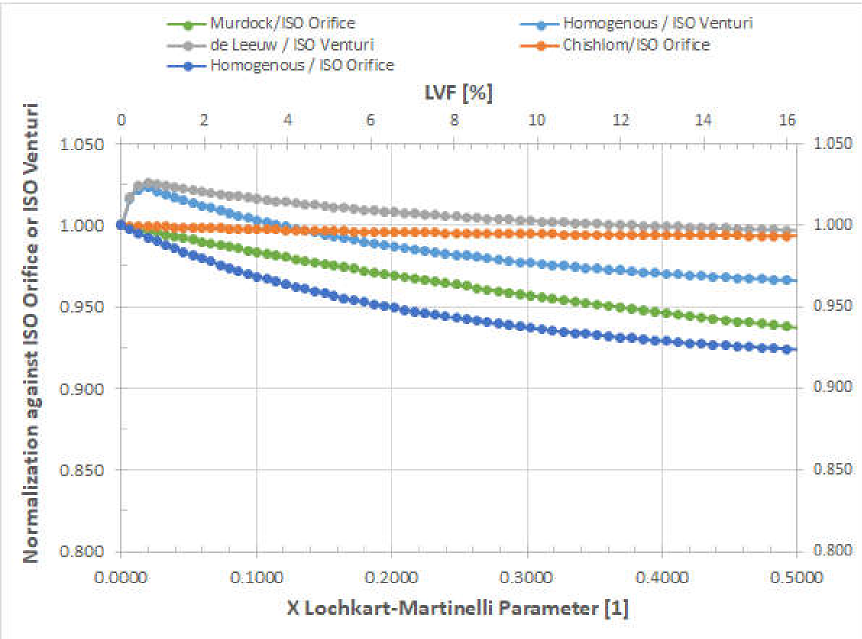

Figure 10: Normalization of the correlation against the ISO 11583 Venturi or Orifice with a gas density 120kg/m3; liquid 800kg/m3, β=0.4, a Froude number=1, the LVF [%] is presented on the upper x-axis.

It can be noted than Chisholm equation which is relatively simple is very well comparable with the ISO 11583 for Orifice at such pressure or density contrast. Venturi correlations against the ISO seems to be slightly overcorrect at very low liquid loading before converging within 1-2%.

The analysis is made now with a Froude number=3. The density of the gas is therefore changing from 30 to 60 and finally 120kg/m^3. It can be noted that in general all correlations excluding de Leeuw (underestimating up to -2.5% at X=0.3) are slightly overestimating the correction against the ISO by less than +2.5%. It can be noted on the figure 11 the trend for the overreading for the orifice and Venturi which start being well distinctive.

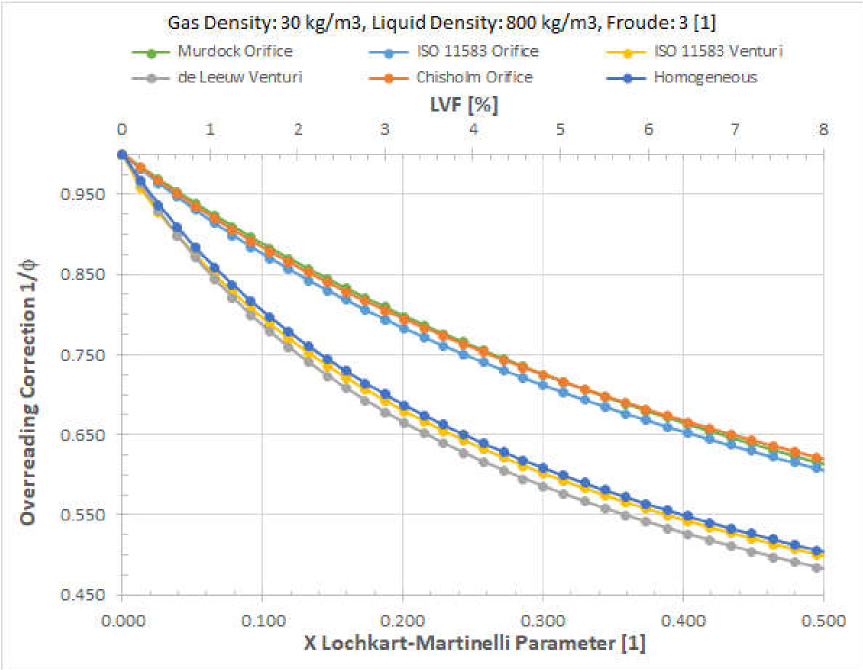

Figure 11: Overreading Correction against the ISO 11583 Venturi or Orifice with a gas density 30kg/m3; liquid 800kg/m3, β=0.4 and a Froude number=3, the LVF [%] is presented on the upper x-axis.

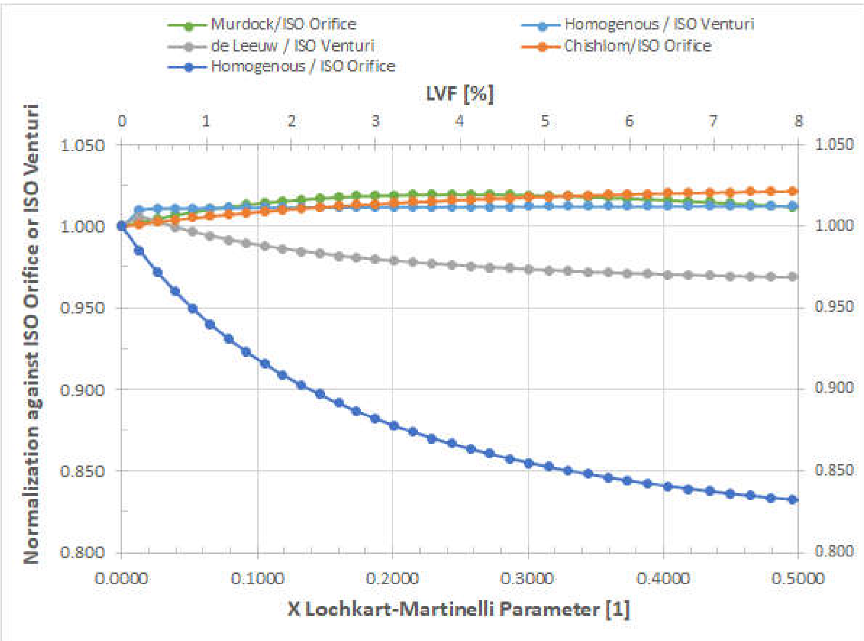

Figure 12: Normalization against the ISO 11583 Venturi or Orifice with a gas density 30kg/m3; liquid 800kg/m3, β=0.4 and a Froude number=3, the LVF [%] is presented on the upper x-axis.

Same trend than see on the figures 11 and 12 above can be noted on the figures 13 and 14 but this time de Leeuw underestimation is much smaller within 1.5%. The Chisholm for Orifice and Homogenous model for Venturi being very consistent with the ISO 11583.
Interesting when the pressure increases the behaviour is the same than before with a clear convergence to the ISO.

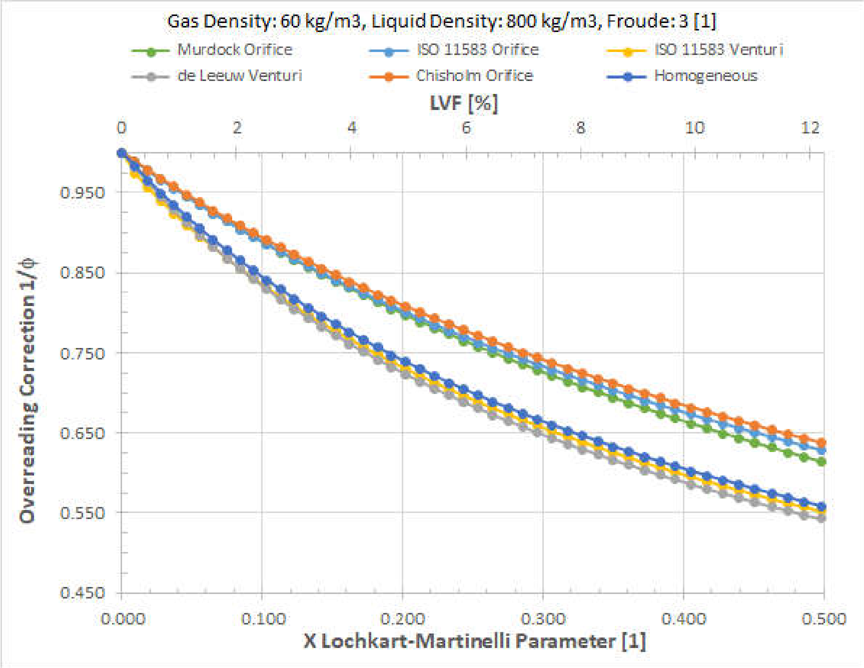

Figure 13: Overreading Correction against the ISO 11583 Venturi or Orifice with a gas density 60kg/m3; liquid 800kg/m3, β=0.4 and a Froude number=3, the LVF [%] is presented on the upper x-axis.

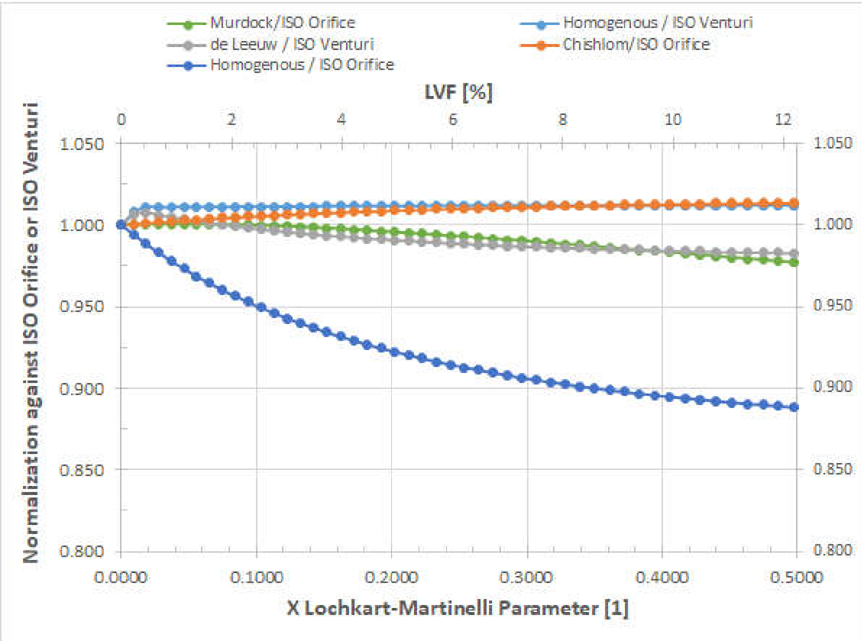

Figure 14: Normalization of the correlation against the ISO 11583 Venturi or Orifice with a gas density 60kg/m3; liquid 800kg/m3, β=0.4 and a Froude number=3, the LVF [%] is presented on the upper x-axis.

In the final case, presented with large Froude number and high pressure (figure 15 and 16), all overreading corrections start collapsing to the same line and therefore closer to the homogenous case. This indicates albeit correlations have multiple parameters to capture some second order phenomena, they are not diverging even looking beyond where they have been built. Murdock is not anymore adequate in this range of conditions.

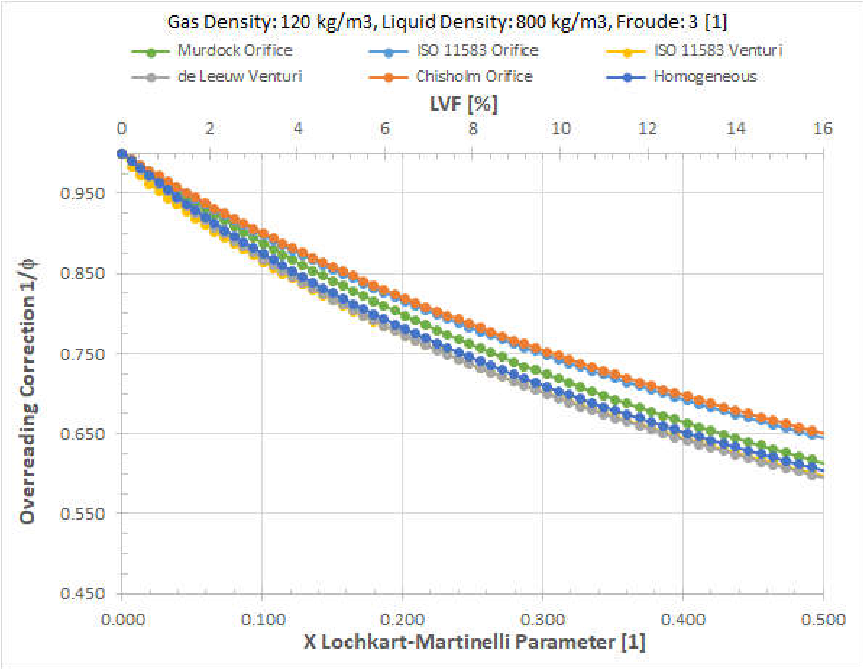

Figure 15: Overreading correction against the ISO 11583 Venturi or Orifice with a gas density 120kg/m3; liquid 800kg/m3, β=0.4 and a Froude number=3, the LVF [%] is presented on the upper x-axis.

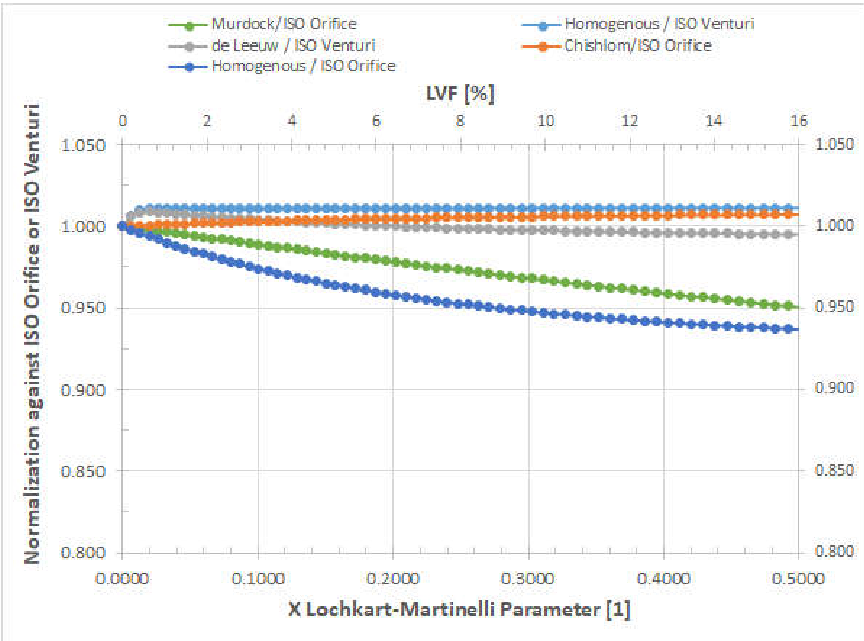

Figure 16: Normalization of the correlation against the ISO 11583 Venturi or Orifice with a gas density 120kg/m3; liquid 800kg/m3, β=0.4 and a Froude number=3, the LVF [%] is presented on the upper x-axis.

7. Takeaway from this analysis

The outcome of this study is to show that all correlations have the same behaviour and then the different variables and parameters introduced over the years are bringing a second order of correction in general. None of them seems to diverge even beyond their domain of development. It is clear also that the homogenous model applied very well for Venturi but does not applied with orifice. We should refrain to use Murdock in general and prefer for quick development

Chisholm. Obviously, there is difference of few percent and this can have a significant financial exposure if the wrong one is applied.

To sum up, with time more and more phenomena have been considered such as gas density, liquid density, WLR, X, Frg and β, the overview of the variables and number of parameters inside respective correlation is given in the table 1 here below. It is highlighted the difference for the Venturi and the Orifice of the ISO11583 writing.

Correlation	Parameters (constant)	Variable (X, β, Frg…)
Murdock O	1	X
Chisholm O	1	X, ρ_l, ρ_g
Homogeneous	0	X, ρ_l, ρ_g
de Leeuw V	3	X, ρ_l, ρ_g, Fr_g
Steven V	12	X, ρ_l, ρ_g, Fr_g
ISO 11583 V	6 to 9	X, Fr_g, ρ_l, ρ_g, β, WLR
ISO 11583 O	3	X, Fr_g, ρ_l, ρ_g

Table 1: Correlations with the number of parameters (fitting coefficient) and the variables, In the table above, the O refers to Orifice plate, and V to Venturi

8. ISO 11583 and added value

Reaching this point, there is something important to understand, to get access to an accurate gas flowrate from a liquid-gas flow in wet gas conditions; it is necessary to know the Lockhart Martinelli parameter which is, by definition, representing the gas wetness which is unknown.

A technique that was developed and refined over the years was to use a tracer, but this is in this case only a spot check and may not be capable to handle the dynamic of the well. It is today used and successfully commercially for accessing not only the liquid rate but also the concentration of condensate and water (MultiTrace from Expro).
The second approach excluding of course the use a separator or sampling techniques was a behaviour noted over the years, showing that the recovery pressure downstream from a Venturi could contain some information about the liquid loading and show that liquid properties can influence the DP overreading. We could mention the work from Steven in this domain from his Ph.D. [5], (NEL 2006) and Reader-Harris et alt [12, 13]. He et alt [10] have done a similar study than for the Venturi and Orifice but for the V-cone in 2012 on the same idea of overreading.
One of the successful uses of this method in a commercial later was with SolartonISA [14] with the use of a differential measurement on straight pipe.

The ISO 11583 is addressing this modelling and providing a self-consistent solution where by using the DP reading, the liquid and gas flowrates can be obtained for "the cost of only" an additional differential pressure transmitter. This is perceived by the author has a breakthrough. In the meantime, if the Venturi is probably the most suitable device for metering in general it generates only low-pressure loss thru the device and an associated low-pressure recovery.
At this stage, there are some recommendations on the distance of the pressure tapping downstream of the Venturi inside the ISO 11583. There is a validity check between the differential pressure recorded at the inlet and the one downstream. Better readings probably than the ISO for people trying to understand more in depth the concept, are the papers published in North Sea Flow Measurement Workshop in 2009 [15] and 1997 [2].

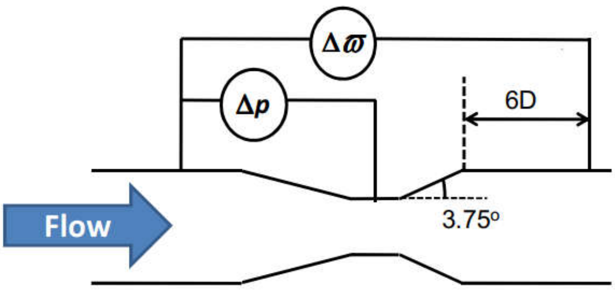

Figure 17: Definition of the variable used in the pressure loss recovery calculation from the ISO 11583.

Meanwhile, the main steps are summarized below and presented in slightly different manner than inside the ISO 11583. The main statement is to show that it is possible to model the Pressure Lost Ratio (PLR) related dry conditions with the factor A_0, B_0, C_0, and a slightly more complex way with "full of liquid" (i.e. for X=0.3).

$$PLR\big|_{dry} = \left.\frac{\Delta\varpi}{\Delta P}\right|_{dry} = A_0 + B_0\beta^{C_0} \tag{28}$$

and
$$PLR\big|_{X=0.3} = \left.\frac{\Delta\varpi}{\Delta P}\right|_{X=0.3} = fn(\frac{\rho_g}{\rho_l}, Fr_g, H) \tag{29}$$

It is then possible to evaluate the factor Y which is the difference of the PLR measurement against the dry case PLR, and Y_{max} which is the difference between the modelling of PLR with X=0.3, and the dry case PLR, and they can be defined by:

$$Y = \left.\frac{\Delta\varpi}{\Delta P}\right| - \left.\frac{\Delta\varpi}{\Delta P}\right|_{dry} \tag{30}$$

and
$$Y_{\max} = \left.\frac{\Delta\varpi}{\Delta P}\right|_{X=0.3} - \left.\frac{\Delta\varpi}{\Delta P}\right|_{dry} \tag{31}$$

and, expressing the ratio Y against Y_{max} as presented below, it is possible to model X versus Froude Number and H:

$$1 - \frac{Y}{Y_{\max}} = \frac{\left.\frac{\Delta\varpi}{\Delta P}\right|_{X=0.3} - \left.\frac{\Delta\varpi}{\Delta P}\right|}{\left.\frac{\Delta\varpi}{\Delta P}\right|_{X=0.3} - \left.\frac{\Delta\varpi}{\Delta P}\right|_{dry}} \tag{32}$$

and to link this ratio with the Lockhart-Martinelli:

$$X = \sqrt[0.75]{\ln(\frac{Y}{Y_{\max}} - 1)\frac{e^{B_1\frac{Fr_g}{H}}}{A_1}} \tag{33}$$

with A_1, B_1 are constant

and
$$X = \sqrt[0.75]{\ln\left(\frac{\left.\frac{\Delta\varpi}{\Delta P}\right| - \left.\frac{\Delta\varpi}{\Delta P}\right|_{X=0.3}}{\left.\frac{\Delta\varpi}{\Delta P}\right|_{dry} - \left.\frac{\Delta\varpi}{\Delta P}\right|_{X=0.3}}\right)\frac{e^{B_1\frac{Fr_g}{H}}}{A_1}} \tag{34}$$

A typical signature for the measured pressure lost ratio is presented on the figure (18) below. It should be kept in mind that the PLR will be affected at least by the gas density, the liquid density, the gas velocity, the β of the Venturi, and the superficial tension liquid gas:

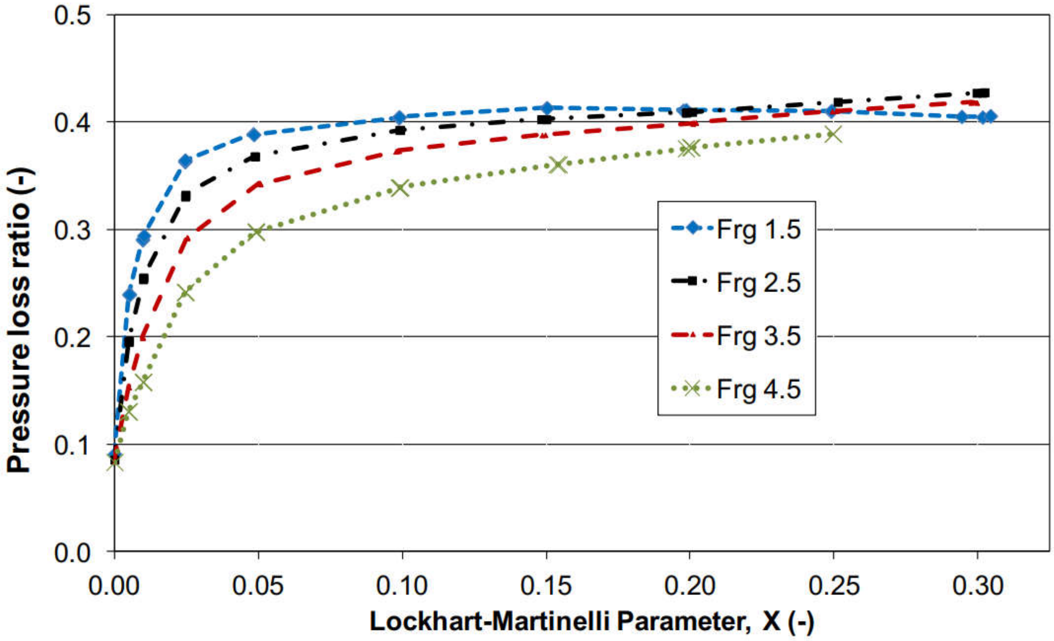

Figure 18: Pressure Lost Ratio measured with a Horizontal Venturi at 30barg [21].

For the orifice plate and without going inside the details the parameter is obtained by

$$X = \frac{C_2}{\beta^{A_2}} Y_o \left(\frac{\rho_g}{\rho_l}\right)^{B_2} = \frac{C_2}{\beta^{A_2}} \left(\left.\frac{\Delta\varpi}{\Delta P}\right| - \left.\frac{\Delta\varpi}{\Delta P}\right|_{Dry\_ISO5167} \right) \left(\frac{\rho_g}{\rho_l}\right)^{B_2} \qquad (35)$$

with B_2, C_2 being constant

The entire question is then to know, if by using this evaluation of X, there an impact on the overall uncertainty for the gas flowrate measurement? The answer is yes, and the ISO 11583 document provides the following table indicating the additional uncertainty on the evaluation of the overreading of ±2.5% to ±4% and lead to an overall performance between ±4 and ±6% versus ±2.5 to ±3% when X is known.

X is known	X≤0.15	X>0.15
Overall Uncertainty	±3%	±2.5%
X is unknown (modelling)	Y/Ymax<0.6	Y/Ymax≥0.6
Overall Uncertainty	±4%	±6%

Table 2: Evaluation of the uncertainty following the evaluation or the input of the Lockhart-Martinelli X

9. Overview of the performance of the main correlations from third party analysis

The description of the ISO 11583 and the other correlations being done, there are numerous works around to review the performance, a quick summary is proposed below and being done either by some research centres developing new correlations or by companies working on commercial product. This is to ensure that the review is fair and as independent as possible. The author would like to indicate that the specific tuned column in the tables below refers to the modification or new correlations proposed by the different authors but knowing that most of them used the entire set of data to tune their set of equation it is not surprising that the overall performance can be better. This is an incestuous process; the proper way will be to keep a set of data representative of the flow untouched (let's say 1/3) of and tuned only over the leaving

2/3 and then verify it over the untouched set. It will be indicated below the table if this process was followed or not.

He et alt [1] review the performance of the ISO 11583:2012 and additionally the 1997 de Leeuw correlation using natural gas with different type of liquid (Venturi size of 4in and 2 or 3 phases), and run at 15, 46, and 72 bara. the Froude number was from 0.59 to 3.634, and X from 0 to 0.266 (GVF was between 0.955% and 100%). Two Venturi were used on CEESI facility with a beta =0.6 (2in and 8in meter or D=49.2 and D=192.7mm). This work was an attempt to develop in this specific range a new model.

Correlation	de Leeuw	ISO 11583	Steven	Specifically Tuned
2.STD DEV	8.74%	2.94%	6.16%	2.70%

Table 3: Performance of the main correlations

A correct statement was made by Boner et alt. [3] revisiting for its application the ISO 11583 and looking for a reduction of the number of input parameters. They use 1,025 data with different fluids for gas (argon, nitrogen), and liquid (water, kerosene, Exxsol D80, Stoddard…). They limit their work to two phases. The β are 0.45, 0.55, 0.60, 0.75, Fr_g is from 0.5 to 4.8, X is from 0 to 0.3 (with 60% of the data below 0.15). It was demonstrated that at low density ratio outside of the ISO standard the correlation was within 4-6% in this case. This work could be considered as an attempt to extend the ISO 11583 and develop a solution for lower pressure. Data have not been reviewed yet. Meanwhile, it is an important point to keep in mind for people expecting to use it at very low line pressure. Assuming a hydrocarbon or liquid density around 800kg/m3 this means that the gas density should be higher than 16kg/m3 or roughly a minimum line pressure higher than 15 bara (ISO 11583).

Correlation	de Leeuw	ISO 11583	Steven	Specifically Tuned*
2.STD DEV	8.6%	2.6%	9.8%	4.0%

Table 4: Performance of the main correlations. *20% of the data where used for validation and revisiting de Leeuw

Collins et alt. [8] had been instrumental in the deployment and development of the wet gas business thru some commercial product since 1990. They have been investing a significant amount of time in data collection to tune their own correlations. It is claimed they have collected more than 5,285 two-phase and three-phase datapoints (almost 50%-50%) with β from 0.55 to 0.70, and meter size from 3 to 10in. Most of the data are with X<0.1 (4,296) and few above 0.3 (59). The interest in this dataset is a cross-facility validation with data from NEL (NMI Primary Calibration Facility & ISO 17025 certified), CEESI (Calibration facility), SINTEF (Research Facility), SwRI (Research Facility), K-LAB (Oil operators), Porsgrunn (Oil operators). This led to the type of gas from natural gas, methane nitrogen, to air; the liquid is fresh water and saline water; and for the oil/condensate from kerosene, Exxsol D80, condensate, hydrocarbon liquid, to drakesol 205. The line pressure was changed from 11 to 235 bara.

Correlation	de Leeuw	ISO 11583	Steven	Specifically Tuned*
2.STD DEV	4.01%	2.58%	4.8%	1.58%

Table 5: Performance of the main correlations. *20% of the data where used for validation (>1,000 data points)

Overall it can be seen that developers (but also end-users) of the wet-gas meters have been carefully looking the performance of such devices based on correlations that needed to be verified or extended to domain of applications not necessarily anticipated initially by the respective inventors. This is obviously one of the drawbacks of using less physics and more

computerized power and curve fitting process, however with more than 8,000 data presented there are some serious trust to be given in the work to establish this new standard ISO 11583. In supplement, this standard is proposing using 2 DP measurements to provide the liquid loading and then the liquid and gas flowrates. This was a breakthrough from the author point of view.
In conclusion, using a simple combination of well-established Venturi design with differential pressure sensors, it is demonstrated the capability to access to liquid and gas flowrates. The uncertainty on the gas flowrate measurement is established between ±2% and ±6% following the quality of the input parameters and well within the performance mentioned earlier for test separator.
The interest in this approach of the wet gas flow metering starting from very dryness conditions to wetter conditions is that some manufacturers try to extend it with larger loading of liquid over the years and then the set of equations describes above led to establish performance beyond the initial wet gas business recommendation, and are capable to address the GVF, today, already down below 90%. Beyond, by extensive test to model some typical flow patterns without necessary addressing the entire physics involved in this domain, solid results were demonstrated which led to commercial acceptance and we believe as indicate later that approach is something more and more acceptable in the new process scheme with digitalization. It should be mentioned that this initiative of understanding of the physics is not and should not be disregarded and it is more a parallel path with some of the main leaders like ONERA, TOTAL [17], and some works from Van Maanen et alt. [16].
The next step for a full 3-phase wet gas flow meter is to have a water cut (or water volume fraction) or water liquid ratio measurement both being linked as presented here below with the set of equations:

$$GVF = \frac{Q_{g\_lc}}{Q_{g\_lc} + Q_{l\_lc}} \tag{36}$$

$$WVF = \frac{Q_{w\_lc}}{Q_{g\_lc} + Q_{l\_lc}} = \frac{Q_{w\_lc}}{Q_{l\_lc}} \frac{Q_{l\_lc}}{Q_{g\_lc} + Q_{l\_lc}} = WLR.(1 - GVF) \tag{37}$$

Different techniques are in use, today, from this point of view, either using electromagnetism with a global or local measurement based on the large contrast from a dielectric point of view between the aqueous phase and the hydrocarbons phase with some carefulness given by Van Maanen [9], or the use of optical solution in the near infrared providing at the relevant wavelength a distinctive signature for the water against the other phases. The use of such type of technology for water cut meter has been well accepted by the end-user because they can be for most of them capable to be used in horizontal pipe which is one of the easiest ways to find some space to install them on the current or new pipe section.

2. Metering Performance

The work presented above is providing the performance on the correlation and then by extension to the wet gas meter in ideal conditions, this means that the necessary input parameters and other variables are well defined or estimated. This does not present at all the overall performance in the field conditions or anywhere else and this needs to be understood clearly.

1. Overall uncertainty for a multiphase flowmeter

The performance of a wet gas meter or any multiphase flow meter is based on some modelling, and some inputs parameters. A flowloop facility will allow to establish such conditions to address the modelling by providing input parameters with very high-quality uncertainty in well-controlled conditions, and lead to state correctly the thru performance of this equipment, this verification is usually done at line conditions or in an equivalent way by having again an extreme good understanding of the fluid behaviour on the given facilities. This is the purpose of such test or called calibration. Based on some defined similitude numbers like Reynolds number, Froude number, and so on it is possible to establish this performance in controlled conditions. This is done on daily basis at NEL for single phase flowmeter. There is an uncertainty associated with this calibration and this is presented inside the calibration certificate. NEL single phase facility will bring the uncertainty on the measurement below few hundredth of percent (i.e. 0.0x%). The same can be extended to the multiphase and wet gas facility with slightly higher number (i.e. 0.x%). The ISO 11583 state that the uncertainty of this modelling against perfect conditions is within few percent and this was based on large number of conditions (flow, liquid, pressure, velocity…) and could be state as the most optimum solution.

2. Overall uncertainty at standard conditions for a multiphase flowmeter

However, the end-user is interested by the performance usually at standard conditions. This means that the output of the meter will be converted thru some calculations and usually based on a tuning of a cubic equation or equation of state (EOS). This will provide the gas flowrate at standard conditions, but, as example, indicates how much of the condensate in gas phase at meter conditions (P, and T being high versus standard conditions) will become liquid at standard conditions. The set of equation (38, 39, 40) to handle this conversion is given here below and this is representing a large part of the added uncertainty of the performance to a given meter, this is usually underestimated or it is believed that doing a test in real conditions will provide the right statement of the performance but this is not the best approach because very often the reference measurement are not correct in the field and it could be stated (see previously statement about test separator) as high as or higher that the expected new wet-gas flowmeter to test.

The standard and common practise called for at least 3 to 4 times smaller the uncertainty on the reference measurement to ensure the uncertainty associated with the reference measurement can be taken out of the analysis [18]. If this is not the case, then the process is much more complex and will not lead to a true performance statement but a pass/no pass test. This EOS or PVT uncertainty is associated with fluid composition and mass transfer when pressure and temperature are changing. A poor EOS tuning or a poor fluid behaviour package, with a lack of traceability on the software used to tune the equations, can introduce significant additional error [19, 20].

$$Qo_{sc} = b_o.Qo_{lc} + Rgcst.b_g.Qg_{lc} \quad (38)$$

$$Qw_{sc} = b_w.Qw_{lc} + Rgwst.b_g.Qg_{lc} \quad (39)$$

$$Qg_{sc} = b_g.Qg_{lc} + Rogst.b_o.Qo_{lc} + Rwgst.b_w.Qw_{lc} \quad (40)$$

Rgcst is the condensate as volatile phase (gas) which is condensing at standard conditions.
Rgwst is the steam (vapor of water in hot conditions) which is condensing at standard conditions as fresh water.
Rogst is the quantity of gas dissolved in oil which is becoming free gas at standard conditions
Rwgst is the quantity of gas dissolved in water which is becoming free gas at standard conditions
The b factors represent the shrinkage or volume factor for the oil and water (bo<1, bw<1), and the expansion factor for the gas (bg>1).

The overall performance or uncertainty is the combination of all these errors and it is presented on the figure 19 below. On the left side 3 main uncertainties are represented with, first, at the bottom, the instrumentation used (i.e. P, DP, T transmitter and so on which have an uncertainty and this needs to be considered); second, the model uncertainty which is associated with the assumption and diverse numerical calculations. It should be kept in mind in some cases, there are some additional errors which can be also due to averaging techniques used, or data clipping, and so on. This is the type of uncertainty that each manufacturer is working hard on to bring them lower. Third, and the last important uncertainty is at this stage coming from the PVT calculation as presented above. Conversion from line to standard conditions is something that

can follow different processes/paths, different flashes and needs to be well captured. Too often the author has seen direct flash from line to standard conditions when the real process was going thru different separators stages and should have been modelled accordingly.
Let's assume, a wet gas meter has been stated to be able to prove the performance to be within ±1% on the condensate at line conditions. It is tempting to say that the performance will be the same at standard conditions but if the shrinkage factor is not known better than ±4% then the overall uncertainty at standard conditions is ±4.1% (see below the calculation) when it was almost 4 times better at line conditions. The wet gas meter was performing very well but the conversion was wrong or not accurate enough. The propagation of error from line to standard conditions assuming no mass transfer can be modelled simply by:

$$\frac{\Delta Q_{o\_@sc}}{Q_{o\_@sc}} = \sqrt{\left(\frac{\Delta Q_{o\_@lc}}{Q_{o\_@lc}}\right)^2 + \left(\frac{\Delta b_o}{b_o}\right)^2} \qquad (41)$$

And

$$\left(\frac{\Delta Q_{o\_@lc}}{Q_{o\_@lc}}\right) = 1\%; \left(\frac{\Delta b_o}{b_o}\right) = 4\% \rightarrow \frac{\Delta Q_{o\_@sc}}{Q_{o\_@sc}} = 4.1\% \qquad (42)$$

3. How to address the uncertainty and ensure fair statement

The three main uncertainties described above are presented on the left side of the figure 19 and they are cumulative. A subdivision of the them is made to highlight the main factors or components to take care. There is no scale about this overall uncertainty, but it is believed that the representation shows a lower contribution for the primary instrumentation uncertainty, against the data processing including model and assumptions, and finally following the carefulness or not for the PVT tuning to lower the PVT uncertainty contribution. It is this overall uncertainty that needs to be compared with something else being much better in terms of uncertainty to state the true flowmeter performance (factor 3 to 4 better as indicated earlier).

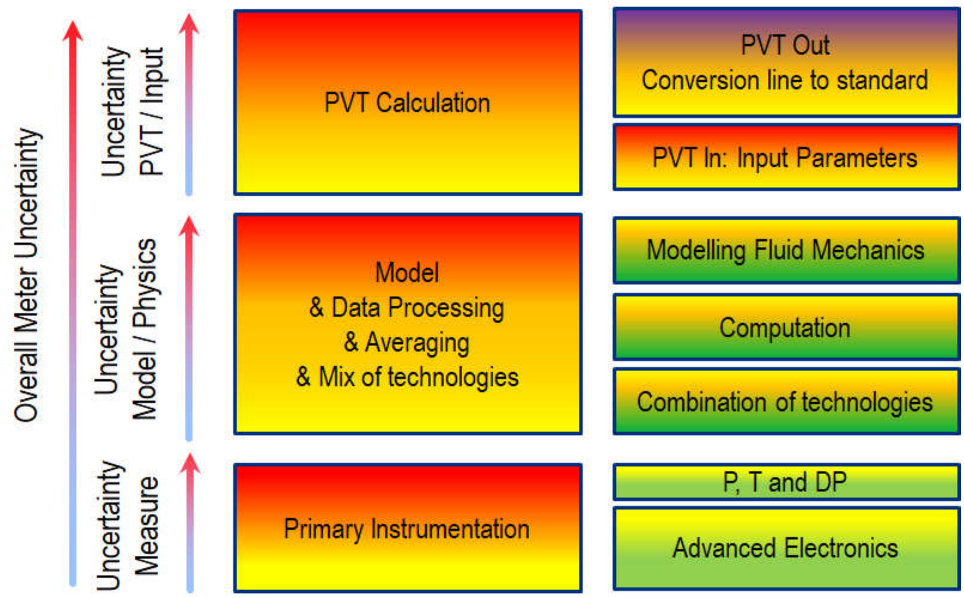

Figure 19: Overall uncertainty for a flowmeter and evaluation of the impact of the 3 mains one highlighted inside the corpus.

The way to proceed and to review the entire performance at NEL is to try to segment the 3 parts of this uncertainty. The PVT part can be audited and verified against traceable PVT package

(DIPPR is one of them, NEL has PPDS which is built like DIPPR built on an internal chemistry database). The interest of this approach is to be able to get the uncertainty of the 11 parameters (oil, water and gas densities, Rgcst, Rgwst, Rogst, Rwgst, bo, bw, bg and in some cases the viscosity either water and oil or liquid) which are required to make the conversion from line to standard conditions (see the description of the equation 38, 39, 40).
The idea, with the use of a flowloop, is to reduce significantly the impact of the PVT package at line conditions and highlighted in purple (figure 20). Still today some people believe that this can be addressed by doing a test with live fluids having some mass phase transfer, but this is not the case at all. It is in fact introducing larger error in the reference measurement, and the conversion from the meter to standard condition (usually some homemade correlations are used) then lead to additional discrepancy.
A flowloop test will address usually what is presented with the green boxes inside the figure 20, the yellow part inside each box is to highlight the quality of the used facility. In the grey box, is the task that should be done to understand the impact of the input parameters true a propagation of error or the use of the wrong setting on the wet-gas meter to see the impact on the results at line conditions. Finally, the third part is what we mentioned earlier with the PVT package and the traceability for the conversion form line to standard conditions.

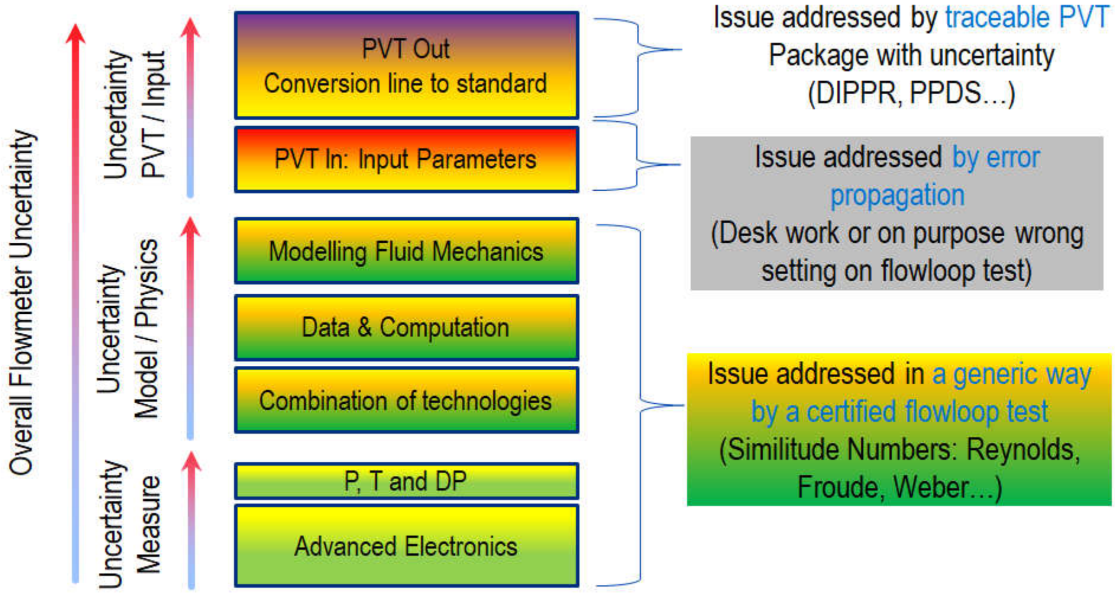

Figure 20: Overall uncertainty for a flowmeter and evaluation of the impact of the 3 main ones highlighted inside the corpus and how this can be addressed.

As conclusion, meter uncertainty is a combination of model assumption, primary instrumentation uncertainty, and not the least PVT uncertainty (conversion from line to standard conditions). The overall reference measurement uncertainty should be, to avoid being considered, 3 to 4 times better than the claimed performance by the new wet-gas product. This means for some of the very advanced product and the correlation presented above with uncertainty within ±2 to ±4%, <u>an overall uncertainty of the reference facility below ±0.5 to ±1%</u>. This shows the challenges for people expecting to conclude with a field test or to highlight the maintenance and quality to have consistently in a facility to ensure to state the best measurement.
The key point for flowloop test is to be able to address the same type of flow regimes than expected in the field conditions with criteria based among them on Reynolds, Froude or others similitude numbers. The flow regime could be also conditioned by adding or not mixer on the facility following the final use of the flow meter, is it just after a choke or a valve? Is it after few elbows? Is it with a large long horizontal section? These are the key input information to consider with the definition of the test matrix to define the proper configuration for the rigging up.

4. How to address the uncertainty and ensure fair statement

From the figure 20 what was left to be addressed is the grey box associated with the input parameters to set the meter, this is an exercise that is important and not presented in the claims of uncertainty up to now. It is usually assumed that the inputs parameters are well-defined, and this is the case in the flowloop and it is a requirement. But this could be misleading to the true performance in any field conditions.
For companies having multiphase metering experts, this can be validated by themselves but if this is left to people without a clear training or ideas of the importance of the input parameters this can lead to output data at line conditions well outside of the expected and claimed uncertainty.

3. Metering Performance

The purpose of this section is to look at the impact of the input parameters on the ISO 11583. The author is not aware of any document addressing this problematic including for the other correlations. The ISO correlation is the latest one and the best publicly available for review. In simple words and in field conditions, the meter will be set or used with some input information (parameters) which cannot be accurate at 100%. What will be the impact of such uncertainty of these input parameters to the output flowrates measurement? What is the most critical parameter to check or verify in the field in case of discrepancy? Is it the density and which one? Or is it the X factor? …

The propagation of error will be done by using the root means square technique. The use of Monte-Carlo simulation could be another way to go thru. The idea of using the derivative is for the future to look at some specific calculations inside the entire process. The strategy is first to identify the true primary parameters, some secondary parameters being dependent of the primary ones should be disregarded as input and then evaluated from the primary ones. Lockhart-Martinelli for example is dependent of the differential pressure ratio, liquid density is dependent of the oil and water density and the WLR. We will not write the entire set of equation and the processing going thru but highlight the main steps. For this paper, the work was only done on the more complex case with the ISO 11583 Venturi correlation.

1. Get access to the set of primary equations.

Here below is highlighted the main equations and then the derivatives associated with them. The liquid density is defined by:

$$\rho_l = WLR \cdot (\rho_w - \rho_o) + \rho_o \qquad (43)$$

Assuming the uncertainty on the density of the water and oil very small (it should be easy to be below 0.2%) then

$$\frac{\partial \rho_l}{\rho_l} = \frac{(\rho_w - \rho_o)}{\rho_l} \frac{\partial WLR}{WLR} \qquad (44)$$

The Lockhart-Martinelli is defined by $X = \sqrt{\frac{\Delta P_l}{\Delta P_g}}$ (45)

and , we could not use the definition of the X given inside the ISO because it is assuming at this stage to know the mass rate of liquid and gas and the derivative is:

$$\frac{\partial X}{X} = \frac{1}{2}\left(\frac{\partial \Delta P_l}{\Delta P_l} - \frac{\partial \Delta P_g}{\Delta P_g}\right) \qquad (46)$$

The value of H was approximated based on discussion to:

$$H = H_w.WLR + H_o.(1-WLR) \quad (47)$$

and $\frac{\partial H}{H} = \frac{H_w - H_o}{H}\frac{\partial WLR}{WLR}$ (48)

The coefficient of revisited Chisholm parameter Cch is defined by:

$$C_{CH} = \left(\frac{\rho_l}{\rho_g}\right)^n + \left(\frac{\rho_g}{\rho_l}\right)^n \quad (49)$$

and we should not forget in this derivation that n is not a constant, and the derivative is:

$$\frac{\partial C_{CH}}{C_{CH}} = \frac{n}{C_{CH}}\left(\left(\frac{\rho_l}{\rho_g}\right)^n + \left(\frac{\rho_g}{\rho_l}\right)^n\right)\left(\frac{\partial \rho_l}{\rho_l} - \frac{\partial \rho_g}{\rho_g} + \ln\left(\frac{\rho_l}{\rho_g}\frac{\partial n}{n}\right)\right). \quad (50)$$

The next evaluation is n which can have two expressions and defined by, it is assumed that the β is correctly defined or another way a proper check is done on the dimension at regular interval in the field:

$$n = \max(n_1, n_2) = \max(A_1^{'} + B_1^{'}\beta^2 + C_1^{'}.e^{\frac{D_1^{'}.Fr_g}{H}}, E_1^{'} + F_1^{'}.\beta^2) \quad (51)$$

and $\frac{\partial n_1}{n_1} = \frac{C_1^{'}}{n_1}\frac{D_1^{'}}{H}Fr_g(\frac{\partial Fr_g}{Fr_g} - \frac{\partial H}{H})e^{\frac{D_1^{'}.Fr_g}{H}}$ (52)

and $\frac{\partial n_2}{n_2} = 0$ (53)

The discharge coefficient has also two possible values following X, and this is defined by

$$C = \min(C_+, C_-) = \min\left(1 + A_1 e^{B_1 Fr_g}, 1 + A_1 e^{B_1 Fr_g}\sqrt{\frac{X}{C_1}}\right) \quad (54)$$

and

$$\frac{\partial C_+}{C_+} = \frac{A_1 B_1 Fr_g}{C_+}e^{B_1 Fr_g}\frac{\partial Fr_g}{Fr_g}; \frac{\partial C_-}{C_-} = \frac{A_1 B_1 Fr_g}{C_-}\sqrt{\frac{X}{C_1}}\left(\frac{\partial Fr_g}{Fr_g} + \frac{1}{2B_1 Fr_g}\frac{\partial X}{X}\right)e^{B_1 Fr_g} \quad (55)$$

The gas mass rate is given by $q_{gas} = \frac{C}{A_1^{''}\phi}\varepsilon\sqrt{\Delta P.\rho_g}$ (56)

and the derivative is obtained by:

$$\frac{\partial q_{gas}}{q_{gas}} = \frac{\partial C}{C} + \frac{\partial \varepsilon}{\varepsilon} + \frac{1}{2}\frac{\partial \Delta P}{\Delta P} + \frac{1}{2}\frac{\partial \rho_g}{\rho_g} - \frac{\partial \phi}{\phi} \quad (57)$$

The correction factor ϕ is defined by $\phi = \sqrt{1 + C_n.X + X^2}$ and the derivative is:

$$\frac{\partial \phi}{\phi} = \frac{1}{2\phi^2}XC_{CH}\left(\frac{\partial C_{CH}}{C_{CH}} + \frac{\partial X}{X}\left(1 + \frac{2X}{C_{CH}}\right)\right) \quad (58)$$

The expansibility factor is defined by $\varepsilon = \sqrt{\frac{K\tau^{2/K}}{k-1}\frac{1-\beta^4}{1-\beta^4\tau^{2/K}}\frac{1-\tau^{(K-1)/K}}{1-\tau}}$ (59)

with $\tau = \frac{P_2}{P_1}$, P3 and P1 being respectively the pressure at the upstream and Venturi throaty, and the ISO 5167 is giving an expression for the derivative:

$$\frac{\partial \varepsilon}{\varepsilon} = \left(\frac{4+100\beta^8}{100}\right)\frac{\Delta P}{P_1}. \tag{60}$$

The density of the mixture is defined by $\rho_m = (1-\alpha_g)\rho_l + \alpha_g \rho_g$ (61)

and the derivative is:

$$\frac{\partial \rho_m}{\rho_m} = \frac{\alpha_g \rho_g}{\rho_m}\frac{\partial \rho_g}{\rho_g} + (1-\frac{\alpha_g \rho_g}{\rho_m})\frac{\partial \rho_l}{\rho_l} + (1-\frac{\rho_l}{\rho_m})\frac{\partial \alpha_g}{\alpha_g} \tag{62}$$

The Froude Number is defined by: $Fr_g = \frac{4.q_{gas}}{\rho_g \pi d^2 \sqrt{g.d}}\sqrt{\frac{\rho_g}{\rho_l - \rho_g}}$ (63)

and the derivative is:

$$\frac{\partial Fr_g}{Fr_g} = \frac{\partial q_{mg}}{q_{mg}} - \frac{1}{2}\frac{\partial \rho_l}{\rho_l}\frac{\rho_l}{\rho_l - \rho_g} - \frac{1}{2}\frac{\partial \rho_g}{\rho_g}\left(\frac{\rho_l - 2\rho_g}{\rho_l - \rho_g}\right) \tag{64}$$

Finally, the GVF is defined by $GVF = \frac{1}{1+X\sqrt{\frac{\rho_g}{\rho_l}}}$ (65)

and the derivative by:

$$\frac{\partial GVF}{GVF} = \frac{-X\sqrt{\frac{\rho_g}{\rho_l}}}{1+X\sqrt{\frac{\rho_g}{\rho_l}}}\left(\frac{\partial X}{X} + \frac{1}{2}\frac{\partial \rho_g}{\rho_g} - \frac{1}{2}\frac{\rho_l - \rho_o}{\rho_l}\frac{\partial WLR}{WLR}\right) \tag{66}$$

The entire set of equations being established, now the process will be to write properly the dependency to the primary variables, some second derivative will be necessary and some equalization and this is not presented here. The main difficulty is to express the uncertainty of Froude number Fr_g. This is because some max or min of set of data needs to be taken into account and lead to different options, however it can be generically written that the uncertainty on the gas mass flow rate is defined by:

$$\frac{\partial q_{mg}}{q_{mg}} = Q_1\frac{\partial \varepsilon}{\varepsilon} + Q_2\frac{1}{2}\frac{\partial \Delta P}{\Delta P} + Q_3\frac{\partial \alpha_g}{\alpha_g} + Q_4\frac{\partial \rho_g}{\rho_g} + Q_5\frac{\partial X}{X} + Q_6\frac{\partial WLR}{WLR} \tag{67}$$

The uncertainty on the gas volumetric flowrate by:

$$\frac{\partial Q_g}{Q_g} = Q_1\frac{\partial \varepsilon}{\varepsilon} + Q_2\frac{1}{2}\frac{\partial \Delta P}{\Delta P} + Q_3\frac{\partial \alpha_g}{\alpha_g} + (Q_4 - 1)\frac{\partial \rho_g}{\rho_g} + Q_5\frac{\partial X}{X} + Q_6\frac{\partial WLR}{WLR} \tag{68}$$

The uncertainty on liquid volumetric flow rate by:

$$\frac{\partial Q_l}{Q_l} = Q_1\frac{\partial \varepsilon}{\varepsilon} + Q_2\frac{1}{2}\frac{\partial \Delta P}{\Delta P} + Q_3\frac{\partial \alpha_g}{\alpha_g} + (Q_4 - 1 + \frac{1}{2}Q_8)\frac{\partial \rho_g}{\rho_g} + (Q_5 + Q_8)\frac{\partial X}{X} + (Q_6 - \frac{Q_8}{2}\frac{\rho_l - \rho_o}{\rho_l})\frac{\partial WLR}{WLR} \tag{69}$$

The uncertainty on water volumetric flow rate by:

$$\frac{\partial Q_w}{Q_w} = Q_1\frac{\partial \varepsilon}{\varepsilon} + \frac{Q_2}{2}\frac{\partial \Delta P}{\Delta P} + Q_3\frac{\partial \alpha_g}{\alpha_g} + (Q_4 - 1 + \frac{Q_8}{2})\frac{\partial \rho_g}{\rho_g} + (Q_5 + Q_8)\frac{\partial X}{X} + (Q_6 + 1 - \frac{Q_8}{2}\frac{\rho_l - \rho_o}{\rho_l})\frac{\partial WLR}{WLR} \tag{70}$$

The uncertainty on oil volumetric flow rate by:

$$\frac{\partial Q_o}{Q_o} = Q_1\frac{\partial \varepsilon}{\varepsilon} + \frac{Q_2}{2}\frac{\partial \Delta P}{\Delta P} + Q_3\frac{\partial \alpha_g}{\alpha_g} + (Q_4 - 1 + \frac{Q_8}{2})\frac{\partial \rho_g}{\rho_g} + (Q_5 + Q_8)\frac{\partial X}{X} + (Q_6 - \frac{WLR}{1-WLR} - \frac{Q_8}{2}\frac{\rho_l - \rho_o}{\rho_l})\frac{\partial WLR}{WLR} \quad (71)$$

with Q_1, Q_2, Q_3, Q_4, Q_5, Q_6, Q_8 being well defined and not explicitly written in this document. Now it is possible to make a propagation of error on 5-6 parameters following how do we address the Lockhart-Martinelli X factor and assuming the dimensions of the Venturi are well-knowns and the uncertainty on the density of water, and oil are reasonably small (i.e. for example <0.2%). The isentropic factor was also kept to 1.4 for this analysis but it can be changed if necessary.

2. Review of the propagation of errors on a set of volumetric flowrates.

This paragraph is addressing the additional uncertainty on the volumetric flow rate for liquid, gas, condensate, and water versus the 6 parameters mentioned above. It is not the overall uncertainty. Imbedded inside the gas density is the line pressure and temperature (also for the oil and water). The simulation will be done at line pressure of 20, 40, 60, 100 bara. The water density is fixed to fresh water, the condensate is ~700 kg/m3, the ΔP reading is 1,000 mbar, the WLR is assumed to be 10%, the β = 0.5, and the Venturi size is 8in (d=88mm), the temperature is fixed to 60°C. The absolutely uncertainty on the WLR is set to an optimistic 5% on the full range, the ΔP uncertainty is within ±1%, the absolutely gas uncertainty is within ±1 or ±2kg/m3 following some simulations or 2% relative. The relative uncertainty on the Lockhart-Martinelli X will be set at ±1% and ±5% following the cases. The X-axis on all the figures from 21 to 36 is a logarithmic scale representing the Lockhart-Martinelli value from 0 to 0.5.

With a gas density of 20kg/m^3 and a relative uncertainty of X of ±1%, the additional error is less than ±2.5% on the volumetric flow rate of gas (figure 21), the liquid uncertainty is increasing versus X with a value below ±1.5% to ±3% when reaching X=0.3. The additional uncertainty of the oil/condensate is within ±7.7%, due to the low WLR is better to show the absolute uncertainty on the water which is like the oil increasing with X.

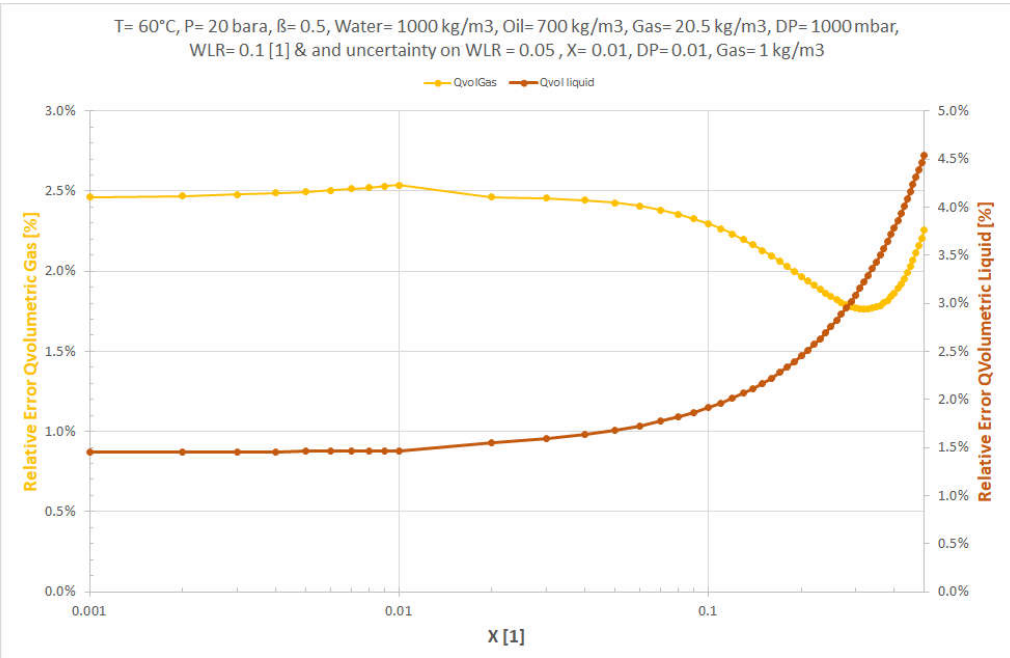

Figure 21: Additional Relative Error to liquid and gas volumetric flowrates due to the uncertainty in the input parameters and specially with line pressure of 20bara, and uncertainty of X=±1%.

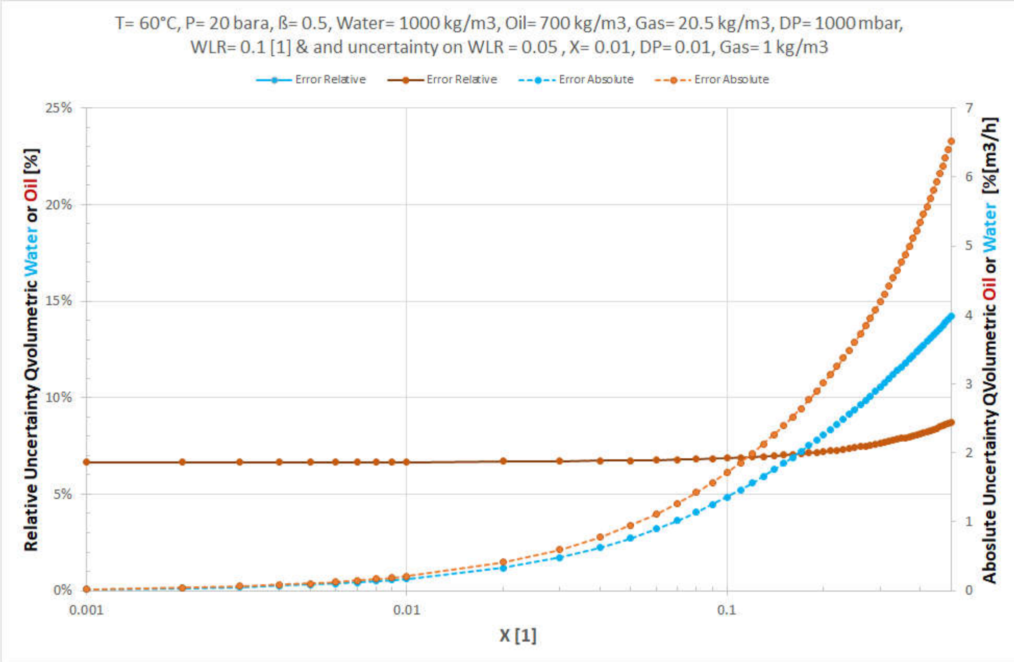

Figure 22: Additional Relative or absolute Error to the water and oil flowrates due to the uncertainty in the input parameters and specially with line pressure of 20bara, and uncertainty of X=±1%.

Increasing the line pressure to 40 bara reduce significantly the additional error on the liquid and gas flowrates, the value come down by a factor 2 for the gas down to around ±1.2% to ±1.3% and reduced by 20% on the liquid to around ±1.5% to <±2.5%. The additional uncertainty on the oil rate stay the same around ±7%.

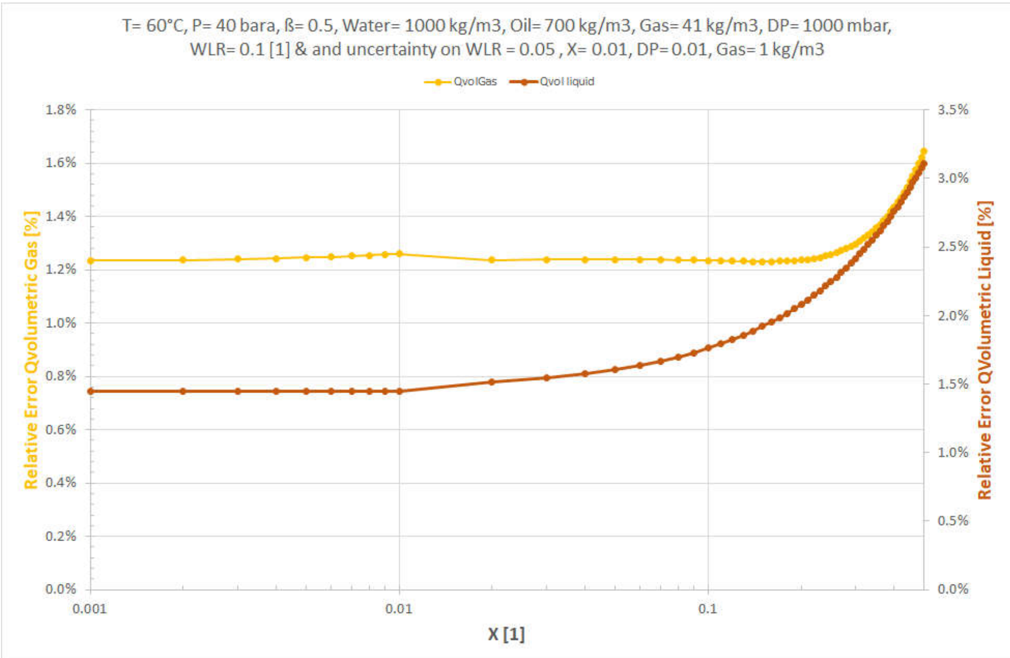

Figure 23: Additional Relative Error to liquid and gas volumetric flowrates due to the uncertainty in the input parameters and specially with line pressure of 40bara and uncertainty of X=1%.

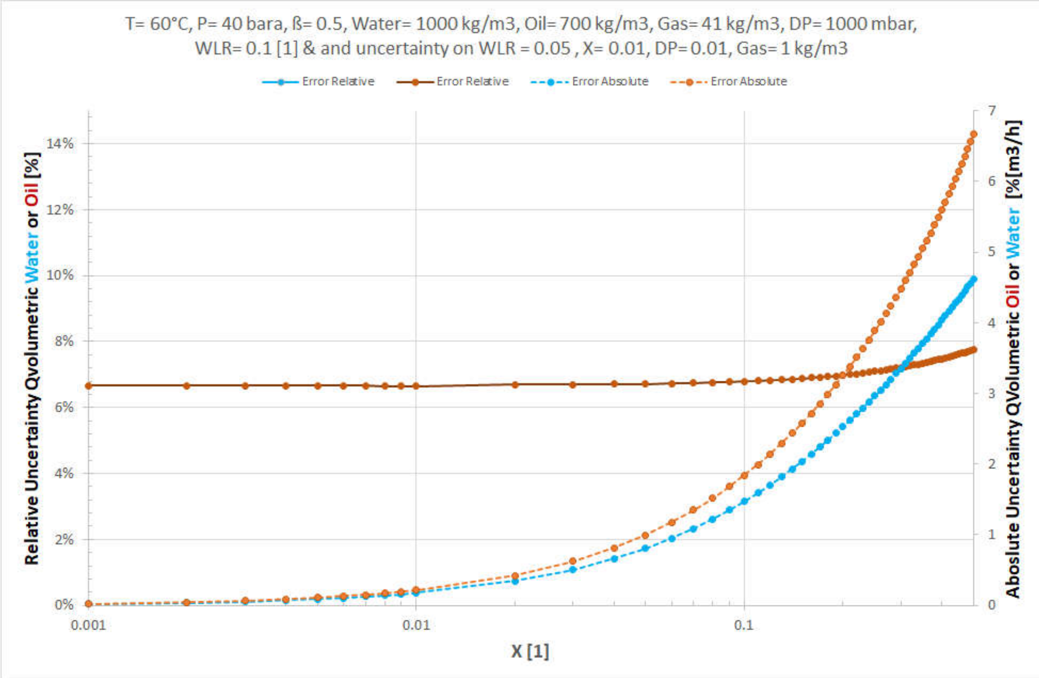

Figure 24: Additional Relative or absolute Error to the water and oil flowrates due to the uncertainty in the input parameters and specially with line pressure of 40bara, and uncertainty of X=1%.

Increasing the line pressure to 60 bara, the additional uncertainty continues to decrease with higher pressure and it is within ±0.8% to ±1% for the gas and form ±1% to ±2% for the liquid. The oil and water stay within the same value ±7%.

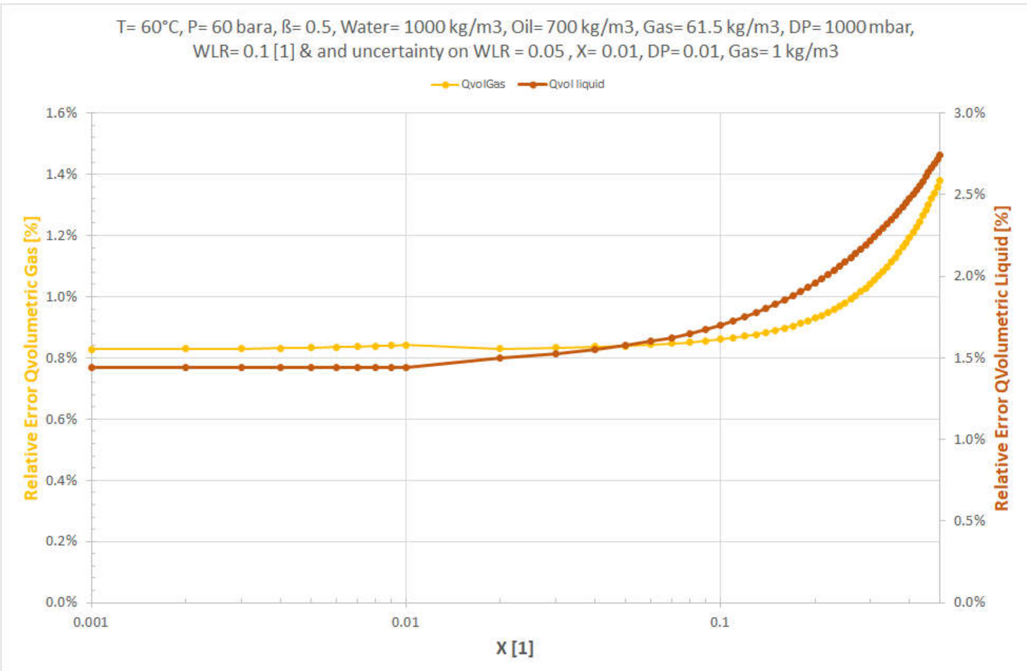

Figure 25: Additional Relative Error to liquid and gas volumetric flowrates due to the uncertainty in the input parameters and specially with line pressure of 60bara, and uncertainty of X=1%.

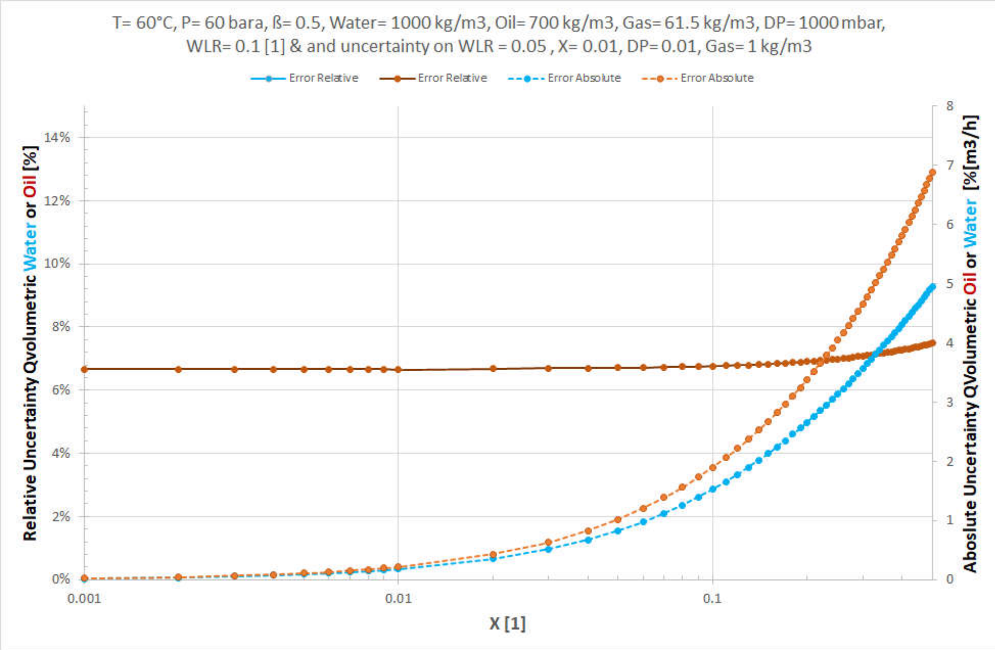

Figure 26: Additional Relative or absolute Error to the water and oil flowrates due to the uncertainty in the input parameters and specially with line pressure of 60bara, and uncertainty of X=1%.

Reaching 100 bara line pressure, the uncertainty is within $\pm$0.5% to $\pm$0.8% for the gas flowrate on the wet gas range with X<0.3 and liquid flowrate well within $\pm$1.5% to $\pm$2%. There is no significant change in the oil and water additional uncertainty.

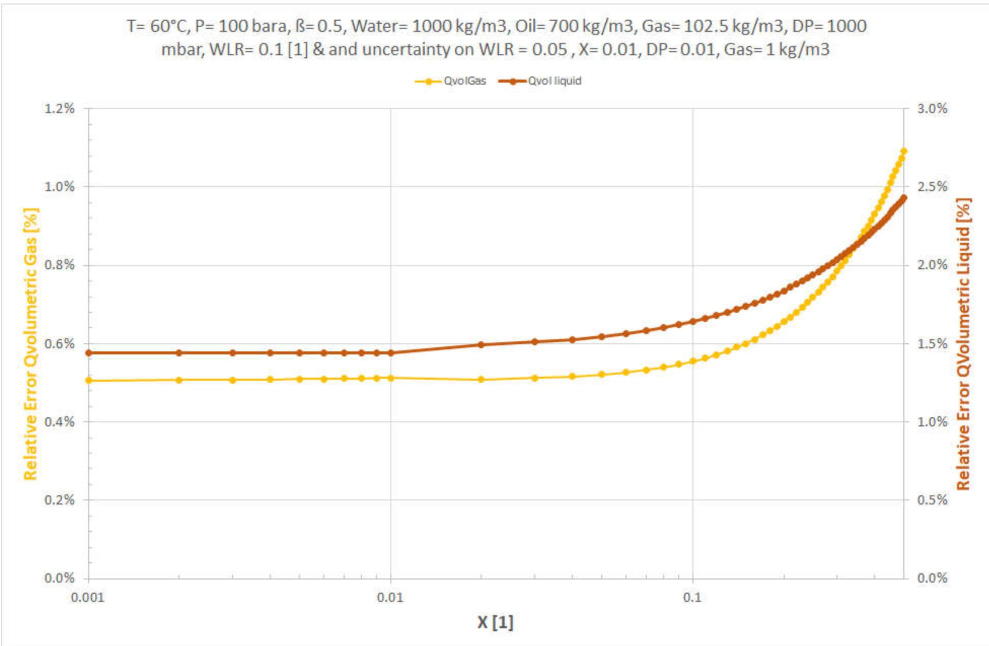

Figure 27: Additional Relative Error to liquid and gas volumetric flowrates due to the uncertainty in the input parameters and specially with line pressure of 100bara, and uncertainty of X=1%.

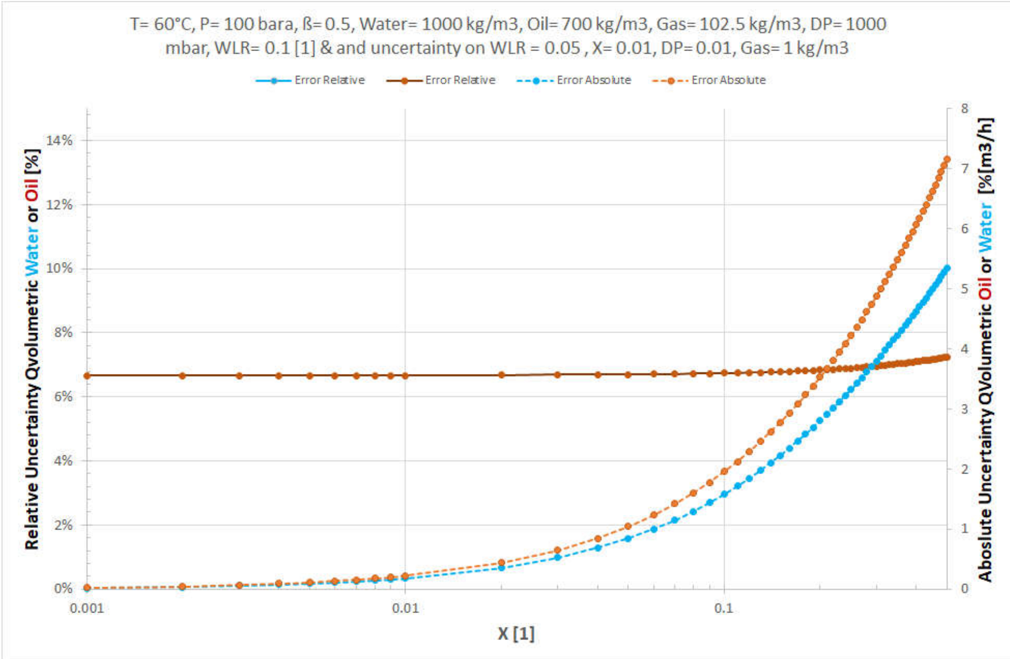

Figure 28: Additional Relative or absolute Error to the water and oil flowrates due to the uncertainty in the input parameters and specially with line pressure of 100bara and uncertainty of X=1%.

The change of uncertainty on the Lockhart-Martinelli immediately impact the additional liquid rate uncertainty (see figure 29 and onward), everything being equal versus the previous study (figure 21 to 28). The uncertainty on the gas flowrate stay the same and close to ±2% for X<0.01 above there is a significant increase and reaching ±8%. The oil and water flowrates uncertainties are increasing in accordance with the liquid uncertainty. The additional uncertainty on the oil is above ±8% and reaching ±13%.

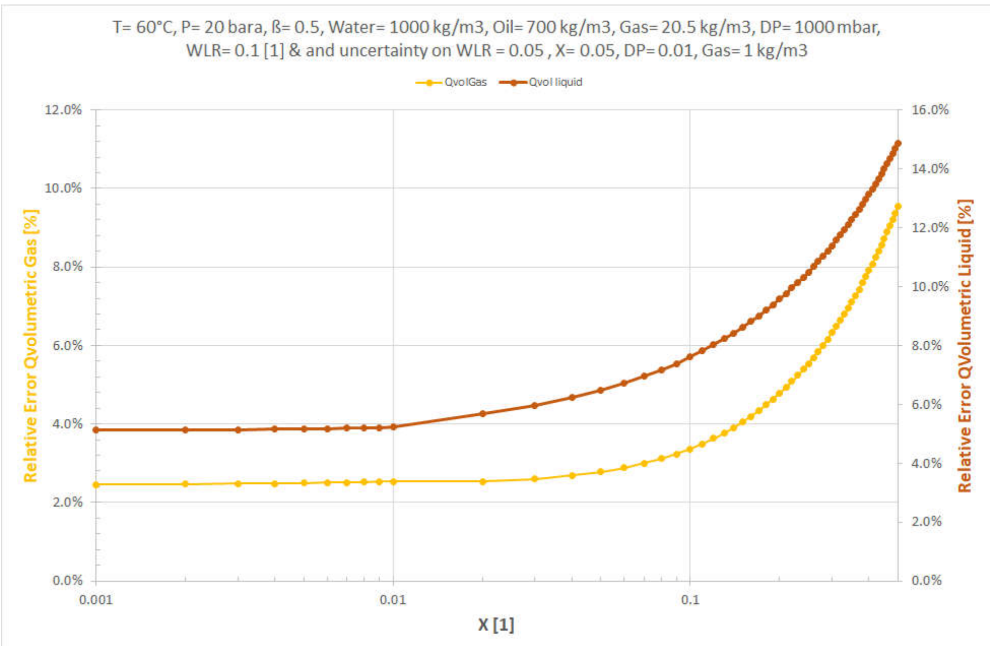

Figure 29: Additional Relative Error to liquid and gas volumetric flowrates due to the uncertainty in the input parameters and specially with line pressure of 20bara, and uncertainty of X=5%.

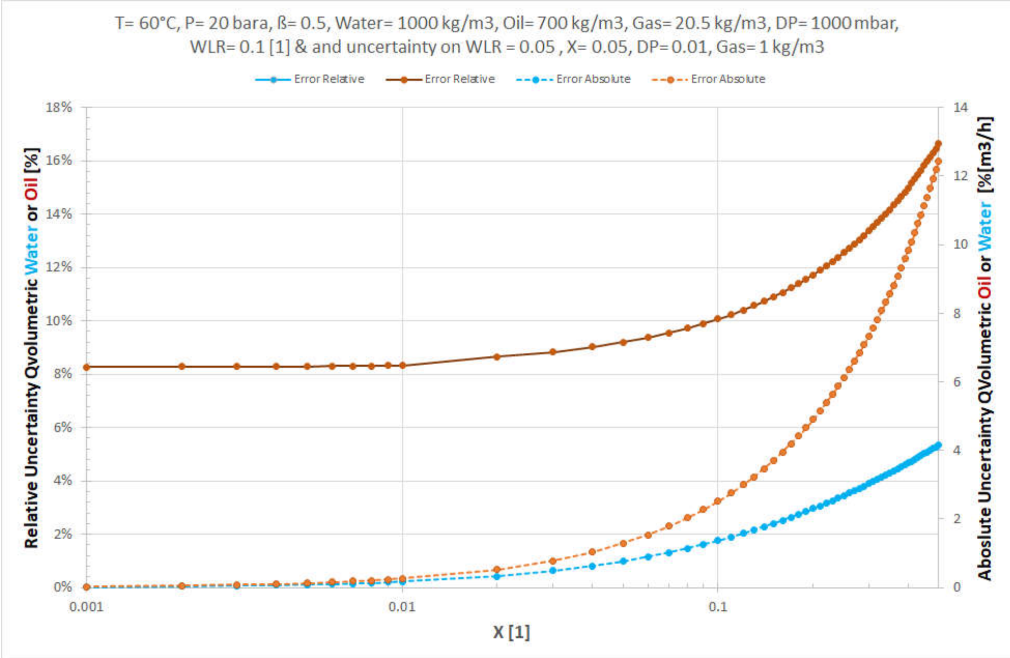

Figure 30: Additional Relative or absolute Error to the water and oil flowrates due to the uncertainty in the input parameters and specially with line pressure of 20bara and uncertainty of X=5%.

As noted previously, the additional gas flowrate uncertainty is becoming smaller with an increase of line pressure from 20 to 40 bara and identical to the uncertainty with X = 1% for X<0.02 and then around ±1%, the increase is more significant with larger X value as anticipated and reach around ±4%. The additional uncertainty on the oil flowrate is from ±8% to 12%.

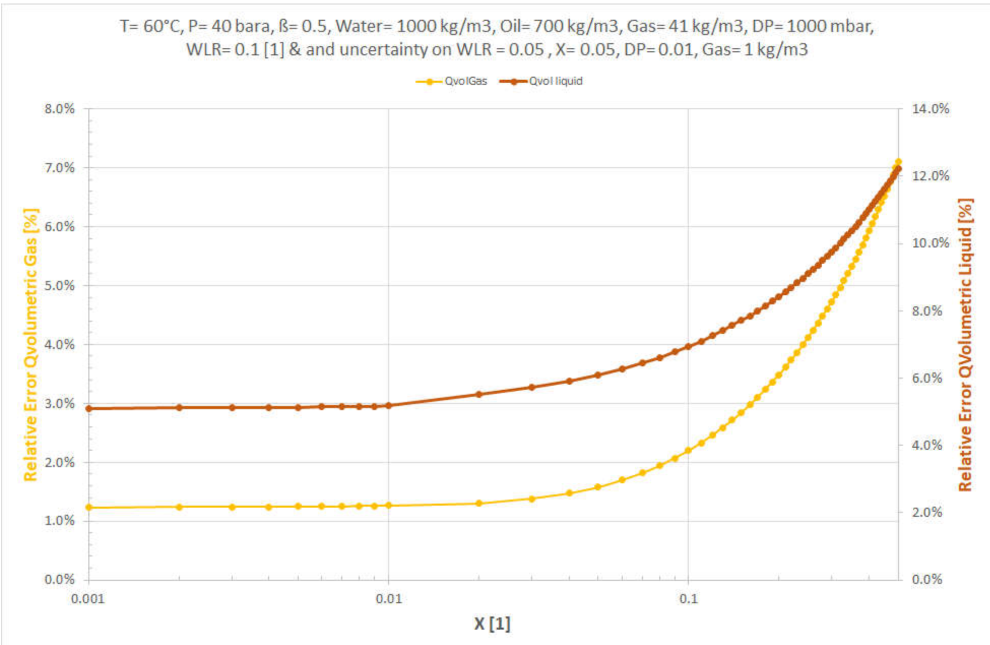

Figure 31: Additional Relative Error to liquid and gas volumetric flowrates due to the uncertainty in the input parameters and specially with line pressure of 40bara, and uncertainty of X=5%.

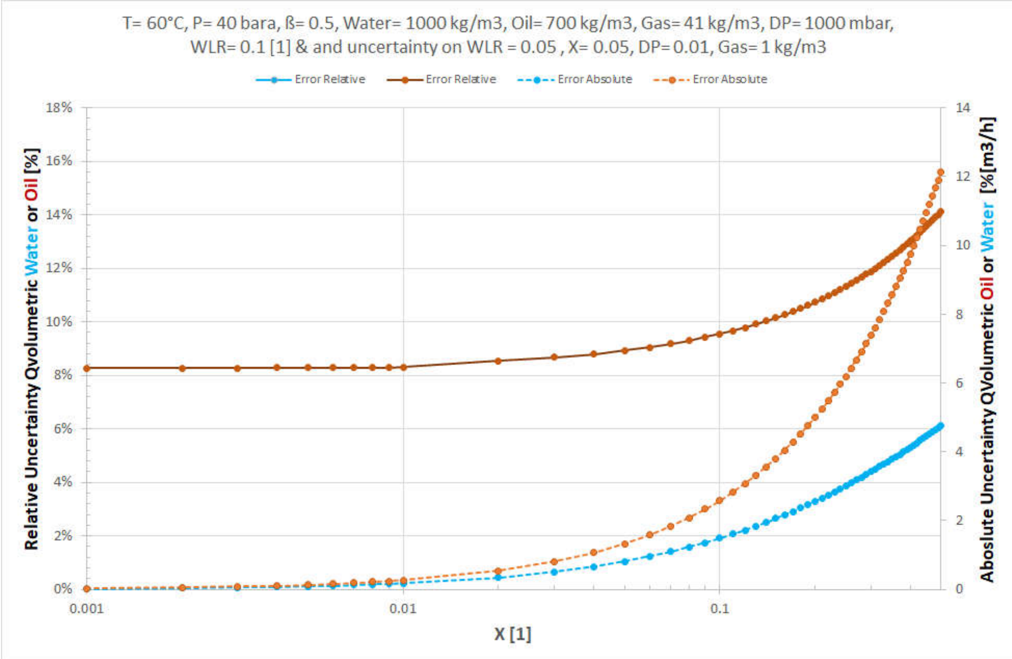

Figure 32: Additional Relative or absolute Error to the water and oil flowrates due to the uncertainty in the input parameters and specially with line pressure of 40bara and uncertainty of X=5%.

Increasing the line pressure to 60 bara, improve slightly the performance for the additional gas uncertainty from less than ±1% to ±4% at X~0.3 which is very similar to the 40bara. The additional liquid flowrate uncertainty does not change significantly too.

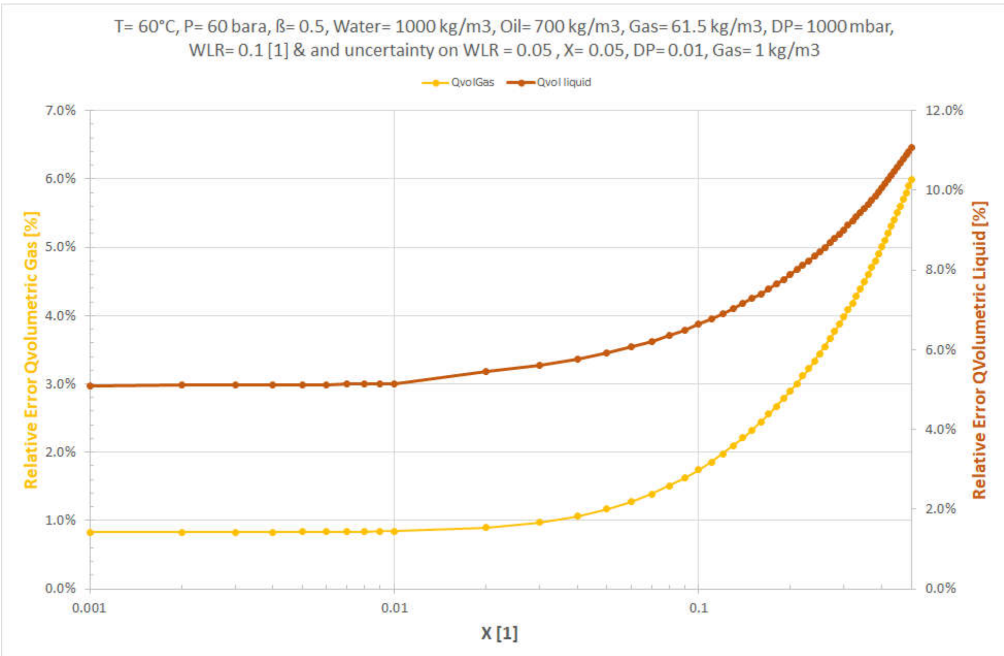

Figure 33: Additional Relative Error to liquid and gas volumetric flowrates due to the uncertainty in the input parameters and specially with line pressure of 60bara, and uncertainty of X=5%.

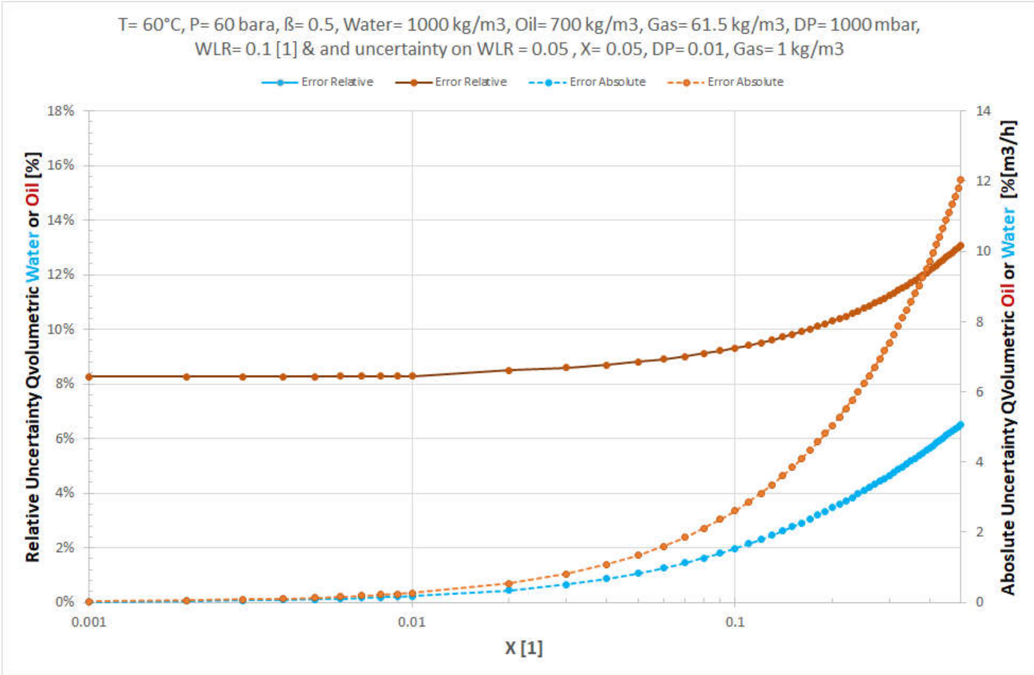

Figure 34: Additional Relative or absolute Error to the water and oil flowrates due to the uncertainty in the input parameters and specially with line pressure of 60bara and uncertainty of X=5%.

Finally, the simulation at 100 bara with ±5% uncertainty on X leads to ±0.5% additional uncertainty at low X and up to ±3% at X~0.3. The additional liquid uncertainty will go respectively from ±2.5% to ±4%. There is no significant change in the additional uncertainty on the oil and water flowrates.

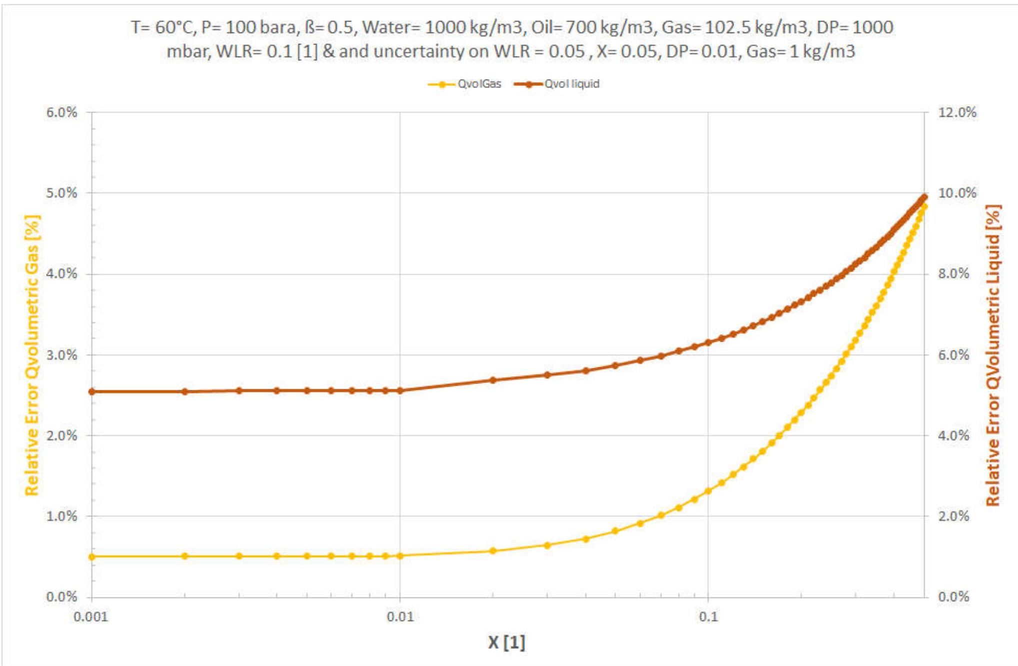

Figure 35: Additional Relative Error to liquid and gas volumetric flowrates due to the uncertainty in the input parameters and specially with line pressure of 100bara, and uncertainty of X=5%.

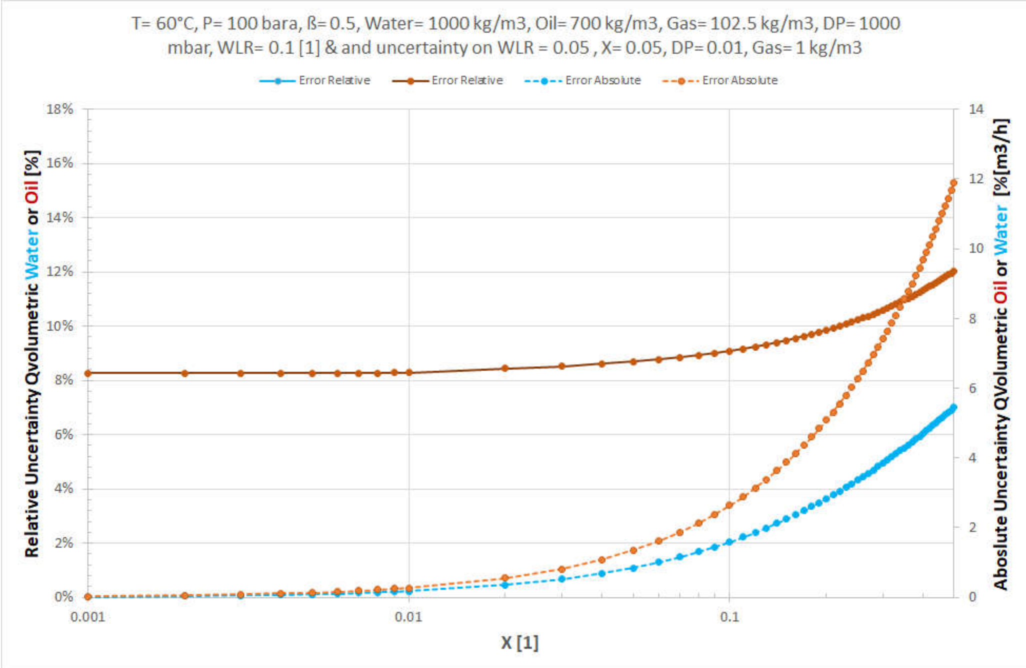

Figure 36: Additional Relative or absolute Error to the water and oil flowrates due to the uncertainty in the input parameters and specially with line pressure of 100bara and uncertainty of X=5%.

3. Overall statement.

To conclude, the propagation of error on the input parameters allow identifying the key measurements to careful review in the field to ensure good measurement. This will not be able to be spot correctly in the case of a field test. We could imagine that the meter was working well (hardware, calculation, assumption being relevant), but it is the set of input parameters that are adding some significant uncertainty. The statement made on the flowloop facility or thru the ISO or any other correlations need to be taken as the correlation performance essentially, and an additional correction factor must be applied specially if the maintenance or the evaluation of the fluid properties is not made regularly, or the flowmeters are difficult to access.
The ISO 11583 is very stable within the overall range addressed in this document and it is a very robust set of equations at high pressure and, whatever the uncertainty on the Lockhart-Martinelli (tested in this document up to $\pm$5% relative uncertainty), the additional uncertainty for the gas flowrate is very small usually <$\pm$0.75%. For the liquid this value is between $\pm$2.5% to $\pm$5.0%. At lower line pressure and close to the limit stated in the ISO, the additional gas uncertainty could be larger than $\pm$2% for large value of Lockhart-Martinelli. For the liquid this additional value is now between $\pm$ 1.5% and $\pm$ 3%.
It is also demonstrated thru this quick analysis that going beyond the X=0.3 can lead to extra additional uncertainty, and this should be well understood specially at low line pressure. Proper input parameters are essential in these cases. Improving the wetness uncertainty or Lockhart-Martinelli number and working with high pressure are the key to correct statement on the gas and liquid flowrates.
The uncertainty on the liquid, water and oil is highly dependent on the Water Liquid Ratio (WLR) or on the Water Volume Fraction (WVF). This is where the focus should be done when 3 phases are expected rapidly from the production or a provision for the installation should be made as early as possible in the design to add such water-cut equipment when necessary.

The work presented, in this chapter, is a fundamental add-on that should be done to any validation of manufacturer products. There is no flowloop that can address the need of each end-users, there is no facility in the field including separator capable to achieve now the level of uncertainty claimed by some wet gas manufacturers (i.e. < ±2% for the gas flowrate) which

means having uncertainty of the single-phase flowmeter reference way better than ±0.5% to ensure that the overall uncertainty under pressure and temperature stays within ±0.5% to ±0.7% maximum. The true metering performance can be done only in controlled conditions stating essentially at line conditions what a flowmeter is capable to achieve in the best conditions.
This performance statement or verification should be based on a proper development and used of a test matrix in adequation with the final use (relevant Reynolds, Froude Number…). Additionally, an analysis about the input parameters and the associated error propagation should be done. This could be achieved either by on purpose setting of the meter wrongly during some flowloop test or by using a playback software by a third party to establish the propagation of error. This needs to be outside of the hand of the manufacturer to provide a fair and impartial statement.
Finally, as presented above the conversion of the performance at line conditions to standard conditions needs to be done thru the propagation of error on the equations associated with the PVT, and these uncertainties on the PVT inputs should be checked against some traceable PVT/EOS software. No facility can have the same fluid than in the field and it is by desk work that this exercise can be done and correctly traceable. There are, today, still too many EOS software built on the use of correlations and assumptions from the literature but not traceable properly. This scientific way to address the entire performance of a flowmeter (wet gas or multiphase) is summarized by the figure 20.

4. DISCUSSION:

The wet gas metering business started from simple concepts, with well accepted technologies and some correlations/models which were reviewed by the community in one way or another. Most of the multiphase meters are built based on the use of a Venturi allowing to address the total mass rate which is based on the use of the Bernoulli's equation as introduced before but on purpose selecting the wrong density at the throat of the Venturi (density of the gas and not the density of the mixture) for wet gas business. This approach has been used even today for on purpose wet gas 2 or 3 phases flows. We have demonstrated that rewriting the equation in a different way could highlight the development of a slip law or Gas Volume Fraction with some specific corrections based on the work done over the years by the inventors and using no additional parameter than the one defined in the definition of the factor "n".

The work to establish the ISO 11583:2012 and the validation with more than 8,000 datapoints presented indirectly in this document on all main facilities around the world is demonstrating the robustness to use it and it is superior quality (and this is normal) to the previous correlations by having more physical variables inside. The ISO 11583 is allowing to use a non-proprietary data computation process and then showing much more transparency and quicker adoption by the end users by presenting the entire data processing and leading to go against the dogma of black box as too often seen at the contrary in multiphase business.

The improvement on the ISO performance is reaching almost a factor 2 against the previous best correlations. The author is considering this effort as a main step forward for the oil and gas industry but as shown in this document and already stated by a manufacturer based on its work there is capability to go further and to reduce by almost another 50% the uncertainty, or to extend the range of validity of the current equations inside the ISO 11583 as indicated by some other manufacturers. The gas flow rate uncertainty is today well within ±2-4% as stated in the ISO and the liquid is in a reasonable value.
The additional work spent to split the entire correction factor to one associated with the discharge coefficient and one with the overreading is going in the right direction from a scientific point of view. The development of a solution for orifice and Venturi in a same document is something new and allowing to show clearly the difference between the equipment and the with the previous works. The author has seen too often the use of correlations with the wrong devices (Orifice when it should be Venturi or the opposite) and "free" assumptions made on the

performance even if the inventors had made some careful statements in their publication. The ISO 11583:2012 has also a range of application well-defined, and it should stay within this limit unless data are recorded and published to demonstrate the robustness where few manufacturers are working already.

This led to acknowledge some serious basis for development of solutions albeit it could be said that more science should/could be introduced. This is probably the limit in the approach of a solution with correlations. In this oil and gas digitalization world, can we try to bring more physics at all cost? Some efforts have been listed and are ongoing in parallel in this wet gas domain from the modelling side (Azzopardi et al.), or some oil and gas companies (TOTAL, SHELL) and finally from the metering side (Van Maanen et al.) and they are proposing some way forward. This shows the dynamic and the continuous interest in this wet gas domain.

This dynamism could be highlighted also by the activity in the development of water volume fraction or water cut over the last 5 years showing a large interest to provide a 3-phase solution for wet gas with cost effective solution as the main driver.
Finally, the trend is to be able to access the larger liquid loading and way above 10% (or GVF<90%) showing an indication of healthy products which could address a bigger market size over the coming years.

With such dynamism and high activity, we believe that joint industrial project (JIP) with the engagement of oil and gas companies and independent laboratories to rank them will help to define the sweet spot for each of them without any doubts on the capability to use them for some new field developments or to replace in some cases old oversold product. This will also reduce the impact of the sales pitch and provide a better understanding to the end-user of what to ask or to listen.

5. CONCLUSIONS:

End-users are starting to understand that there is not a universal multiphase meter on the market today capable to address the entire multiphase and wet gas business albeit the sales pitch from some companies will try to demonstrate the opposite. There are different robust solutions following the fluid properties changes that multiphase flow are facing.

Up to now, to use the correlations with wet gas meters, it was necessary to have access to the wetness input, which is something that the end-user was expected to get. The way to handle it was to use either a tracer technique or to take a different approach with the use of a multiphase meter developed in this wet gas domain of application. Unfortunately, these types of multiphase flow meters are expensive not necessary more accurate in high GVF than simple solution based on the combination of such correlations and Venturi. Worst, most of them are requiring to be in vertical position leading to higher cost for installation. The ISO 11583:2012 has been capable to address the problematic to get access to the gas wetness or Lockhart-Martinelli parameter and model it for finally providing a self-consistent solution leading to the determination of the liquid and gas flowrate for only the cost of an additional differential pressure transmitter downstream of the Venturi. This is perceived by the author has a breakthrough.

In general, and beyond the wet gas metring, the less complexity of the assembly of technologies and components including known or adopted equations used inside a wet gas flowmeter allows quicker acceptance by end-users and a faster growth. The differentiation in this domain of flow regimes is then the knowhow in the modelling, data analytics among the manufacturers. There are already few manufacturers going beyond the ISO 11583 limit and capable to provide better level of uncertainty on gas, liquid, and obviously with the relevant water cut meter to the 3 phases. The access to the 3 phases is compulsory and the proper understanding of the impact in PVT of fluid behaviour from line to standard conditions, including traceability to access to the overall meter performance.

As a note, it is believed that the end-users should be careful about extrapolation of results, and results obtained with small size meter (i.e. for example 2 to 3in) to larger size (i.e. 6 to 8in or above). It is believed that wet gas flowmeter should be tested in flowloop conditions as close as possible to the field conditions (pressure, flowrates) when it is possible, and using well defined number (Reynolds, Froude…) when it is not possible to match the field conditions. The Computational Fluid Dynamic (CFD) could be use in complement to establish performance beyond the capability of the third-party test facilities.
The improvements in software and/or electronics should lead to gain in uncertainty and robustness but this should be documented and traceable and validated by third party test. By complying with this common sense, this will be pushing even further and quicker the adoption of the wet gas meter. We believe with the the market going forward to cleaner hydrocarbon, it is a good indicator of the expected growing business for such type of equipment.

6. ACKNOWLEDGMENTS:

This work has been achievable thank to the capability given by University of Coventry, NEL to support this idea and providing continuous encouragement. An alteration of some previous works or information have been made to ensure a consistent and sometime simplified message which was provided to the current readers. This document summarizes the main ideas for possible development and reconsideration of the way to address the wet gas business. The presented ideas, statements, or opinions can only engage the author.

7. REFERENCES:

[1] A new correlation for wet gas flow rate measurement with Venturi meter based on two-phase mass flow coefficient – D. He, B. Bo, - Flow Measurement Instrumentation, 2014

[2] Liquid Correction of Venturi Meter readings in wet gas flow – R. de Leeuw - North Sea Flow Measurement, 1997

[3] Generalized Wet Gas Venturi Meter Correlations: Assessment and Improvement – M. Bjoner, P. Fosbol, M. Lisberg, H. Lisberg – North Sea Flow Measurement Workshop, 2017

[4] Wet Gas Venturi Metering – D. Stewart, G. Brown, D. Hodges - SPE 77350, 2002

[5] Wet Gas Metering – R. Steven - Ph.D. University of Strathclyde Scotland (UK), 2001

[6] Research Note: Two phase flow Through sharp-edged Orifices – D. Chisholm – Journal of Mechanical Engineering Science, 1967

[7] Two-Phase Flow Measurements with Orifices – J.W. Murdock – Journal of Basic Engineering, 1962

[8] Evaluating and Improving wet gas corrections for horizontal Venturi meters – A. Collins, M. Tudge, C. Wade – SolartonISA, 2014

[9] Two-Phase Flow Measurements with sharp-edged orifices – Z.H. Lin – International Journal of Multiphase Flow, 1982

[10] A new Model for V-cone meter in low pressure wet gas metering – D. He, B. Bai, Y. Xu, X. Li – Measurement Science and Technology, 2012

[11] Measurement of wet gas flow by means of pressure differential devices inserted in circular cross-section conduits – ISO/TR 11583:2012

[12] Impact of using ISO/TR 11583 for a Venturi tube in 3-phase Wet-Gas conditions – E. Graham, M. Reader-Harris, N. Ramsay, T. Boussouara, C. Forsyth, L. Wales, C. Rooney – North Sea Flow Measurement Workshop, 2015

[13] Wet-Gas Measurement: ISO/TR 11583 – M. Reader-Harris – North Sea Flow Measurement Workshop, 2012

[14] Dualstream 2 Advanced Subsea – SolartonISA, 2012

[15] An improved model for Venturi - The overreading in wet gas – M. Reader-Harris, E. Graham - North Sea Flow Measurement Workshop, 2009

[16] Modelling of Wet Gas Flow in Venturi Meters to predict the differential Pressure – H. Van Maanen, H. de Leeuw – North Sea Flow Measurement Workshop, 2016

[17] Analysis of High-Pressure Test on Wet Gas Flow Metering with a Venturi Meter – P. Gajan, Q. Decaudin, J.P. Couput - HAL-01058403, 2014

[18] A way forward to comparison of MPFM test from flow loop to field conditions considering specific challenges, relevant criteria, and other practical statements to succeed – B. Pinguet, 2017

[19] Optimization of Multiphase Flow Metrology through Accurate Phase-Behaviour Characterization – J. Foster, B. Pinguet, S. Smuk, J. Nighswander – 7th International Conference on Petroleum Phase Behaviour and Fouling - USA, 2006

[20] Criticality of the PVT Model in Multiphase Flow Meters to ensure accurate volumetric flow rate reporting – B. Pinguet , P. Guieze, E. Delvaux – 1st Multiphase Pumping & Technologies Conference – Abu Dhabi, 2004.

[21] Performance of a Vertically Installed venturi Tube in Wet Gas Conditions – C. Mills – Kuwait Flow Measurement Technology, 2015.