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Paper 7.1

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

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1 INTRODUCTION

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

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

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

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

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

2 WET GAS METERING SYSTEMS

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

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

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

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

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

3 WET GAS CHARACTERIZATION

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

3.1 Typical Parameters Used In Wet Gas Metering Area

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

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

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

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

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

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

3.2 Flow Structures In Wet Gas Metering

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

3.3 Reservoir & Composition Perspectives

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

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

4 VENTURI METER CORRECTIONS

4.1 Principle Of Wet Gas Metering Using A Venturi

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

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

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

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

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

In fact the actual mass flow rate of gas is:

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

A correction factor is then introduced:

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

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

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

4.2 Correlation

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

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

$$\phi_g = 1 + 1.26 X_{LM} \quad (7)$$

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

$$K = \frac{\overline{U_g}}{U_l} \quad (8)$$

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

$$\phi_g = 1 + C.X_{LM} + X_{LM}^{\ 2} \quad (9)$$

$$C = \frac{1}{K}\sqrt{\frac{\rho_l}{\rho_g}} + K\sqrt{\frac{\rho_g}{\rho_l}} \quad (10)$$

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

$$\phi_g^{\ 2} = 1 + 2.66 X_{LM} + X_{LM}^{\ 2} \quad (11)$$

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

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In this expression :

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

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

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

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

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

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

4.3 Limitation Of Available Correlations

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

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

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

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

To simulate the two-phase flow phenomena inside the Venturi, it is necessary to take into account the gas/liquid film interaction near the wall, the gas/droplet interaction in the core region and also the mass flux of liquid exchanged between the film and the spray (entrainment and deposition of droplets).

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

5 DEVELOPMENT OF AN ADVANCED CORRECTION SOFTWARE: WEGMOVE©

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

5.1 Flow Modelling For Delta P Measurement Interpretation

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

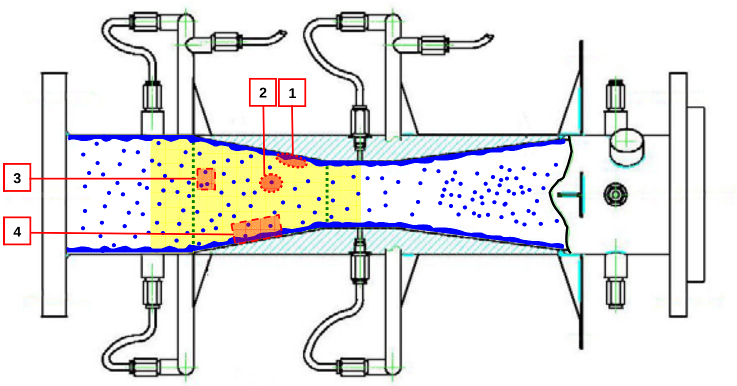

Fig. 1 - Sketch of the gas/liquid interactions in the Venturi meter
1: Gas/liquid film ; 2: Gas/droplets ; 3: Droplet/Droplet ; 4: Droplet/liquid film

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

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

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

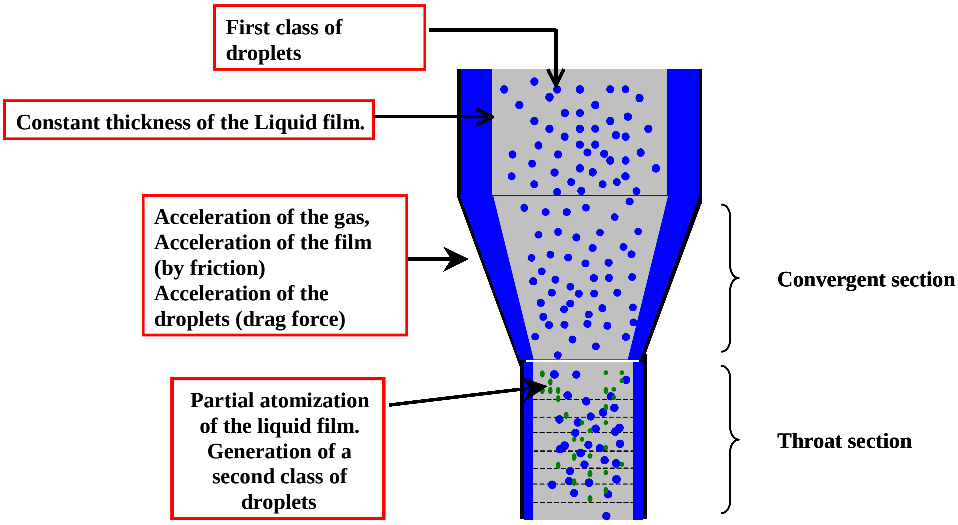

Fig. 2 - The different flow phenomena occurring in the Venturi meter between the two pressure tap

Finally, the following relationship can be written:

$$\Delta P_{WG} = \Delta P_{Bernoulli} + \Delta P_{convergent\_droplets} + \Delta P_{atomization\_droplets} + \Delta P_{liquid\_film} \tag{17}$$

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

5.2 Wet Gas Flow Prediction In Venturi

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

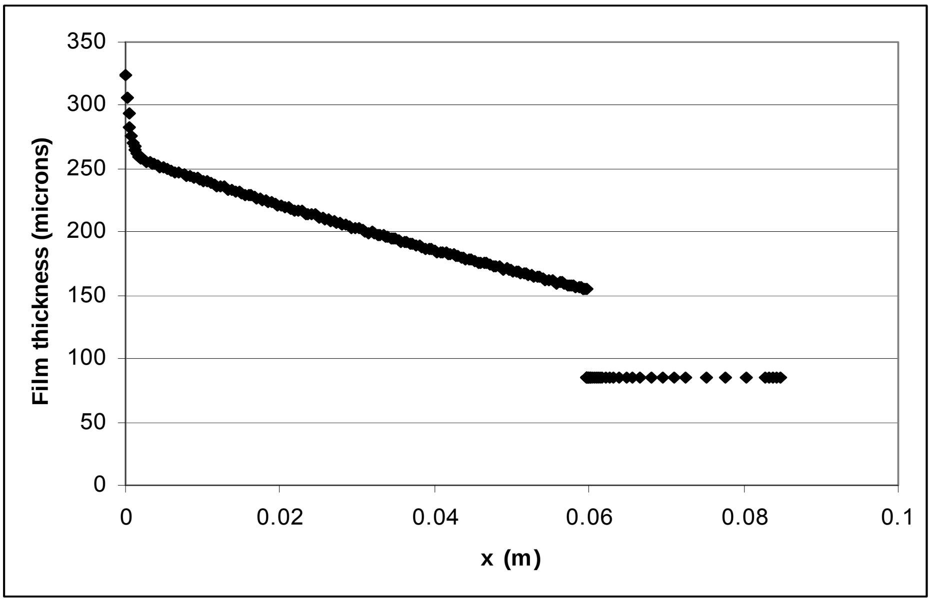

Fig. 3 – Distributionof the film thickness in the venturi meter

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

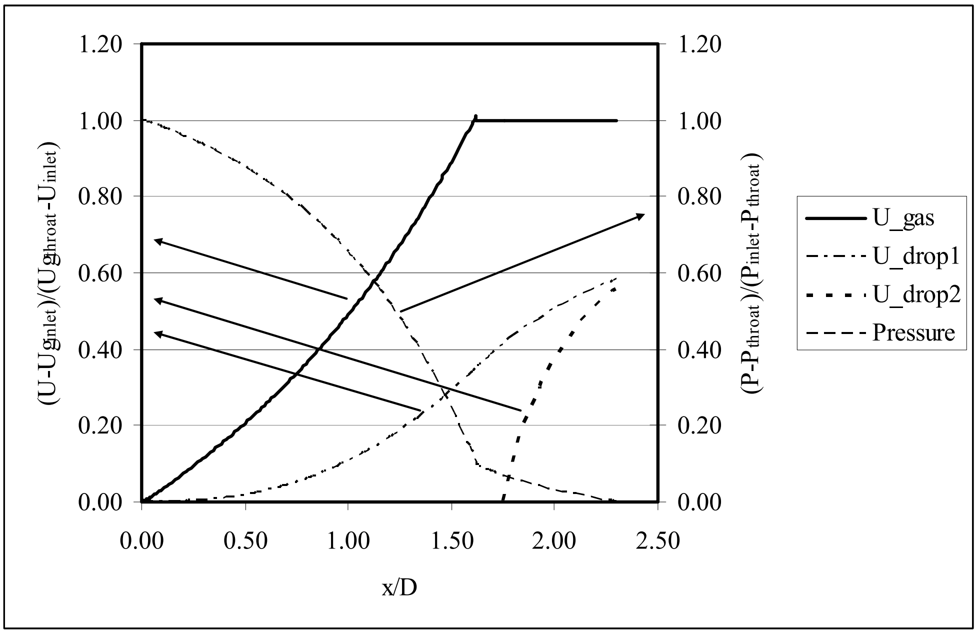

Fig. 4 – Distribution of the gas, entrained droplets and atomised droplets velocities an pressure in the venturi meter

The following aspects of the code can be visualized in figure 4: the gas superficial velocity increases in the convergent section and is constant in the throat section. The gas/droplets interaction induced a concomitant acceleration of the droplets in the convergent section and in the throat. The atomized droplets velocity is non-zero number from the beginning of the throat and then increases toward the value of the gas velocity. On the pressure curve, we observed that even if the gas velocity is constant in the throat, the pressure continues to decrease due to the droplet acceleration in this pipe venturi part.

5.3 Venturi Flow Rates Calculation Using WEGMOVE Model

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

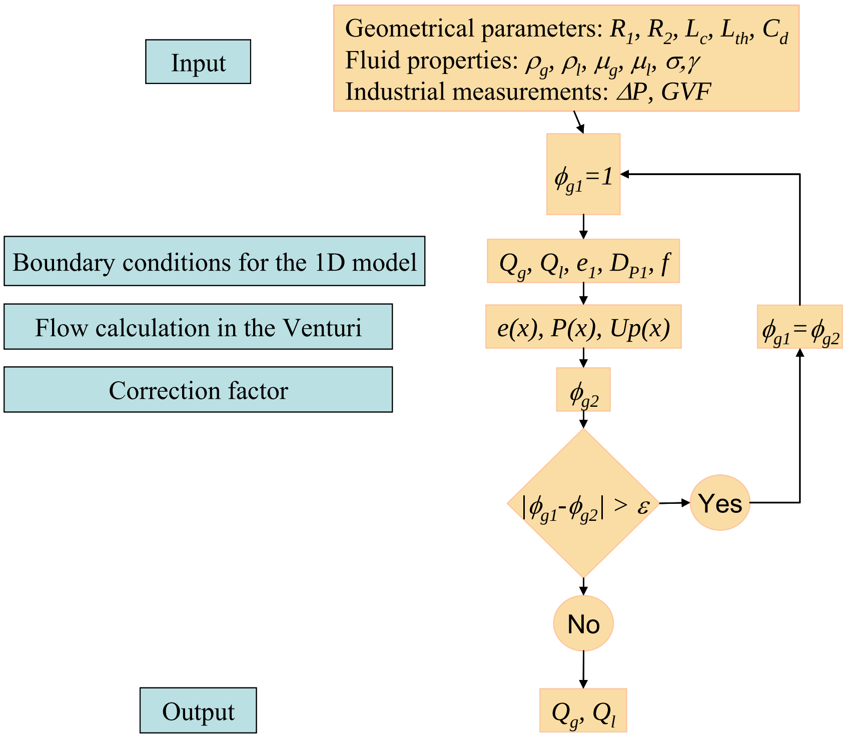

Fig. 5 - Flow chart of the WEGMOVE © code

Boundary conditions determination from industrial inputs:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$WC = \frac{Q_w}{Q_o + Q_w} \qquad (22)$$

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

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

$$\rho_l = \rho_w.WC - \rho_o.(1 - WC) \qquad (23)$$

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

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

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

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

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

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

6.1 Low Pressure Tests

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

Table 1 – Characteristics of the low pressure tests

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

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

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

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

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

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

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

$$\mu_l = WC.\mu_w + (1 - WC).\mu_o \qquad (27)$$

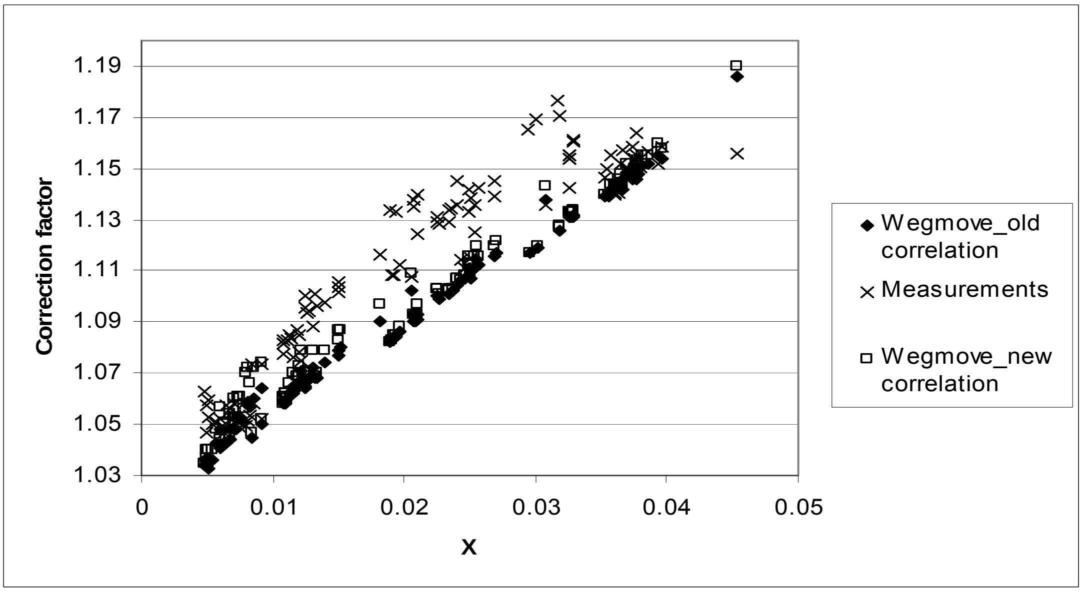

Fig. 6: Comparison old/ new correlation in WEGMOVE

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

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

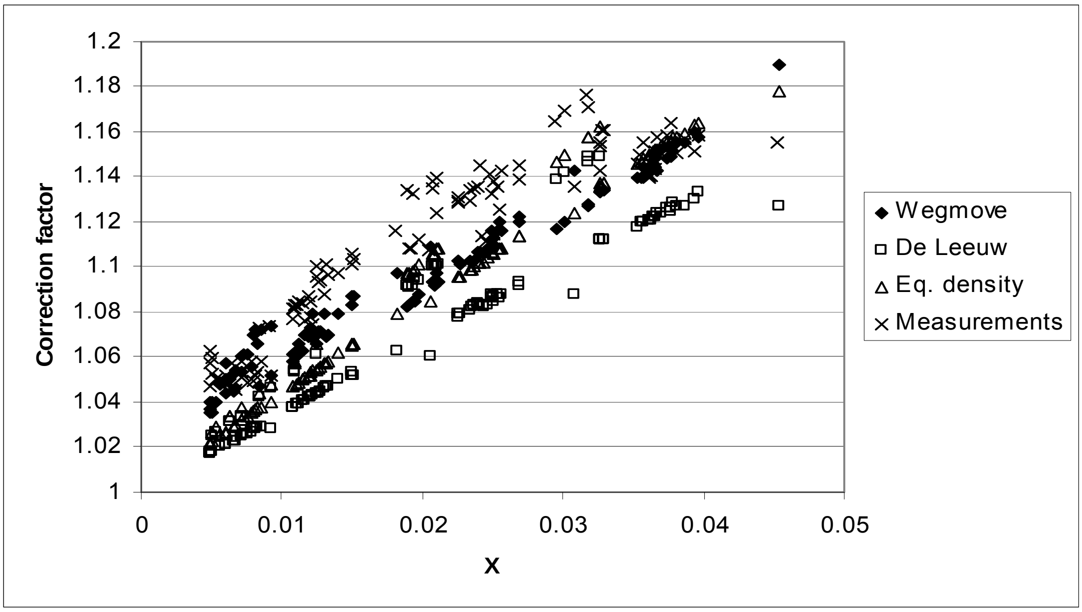

Fig. 7: Comparison of the results obtained by different calculations, for the low pressure tests

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

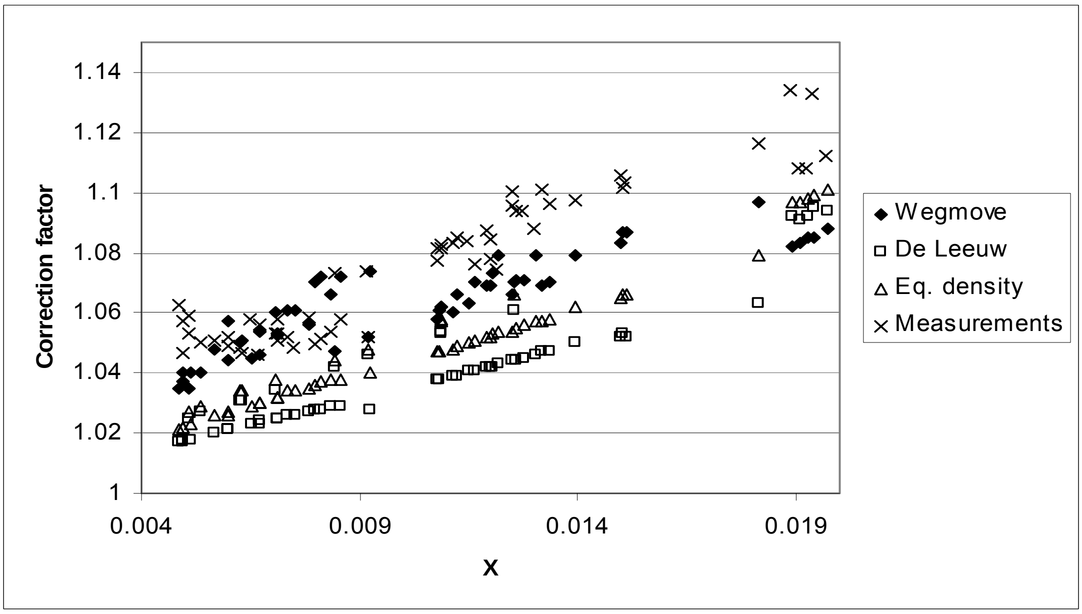

Fig. 8: Comparison of the results obtained by different calculations, for the low pressure tests and type I wet gas

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

6.2 High Pressure Tests

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

Table 2 – Characteristics of the high pressure tests

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

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

6.2.1 Tests in two phase flow with one liquid component:

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

6.2.2 Tests in two phase flow with two liquid components:

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

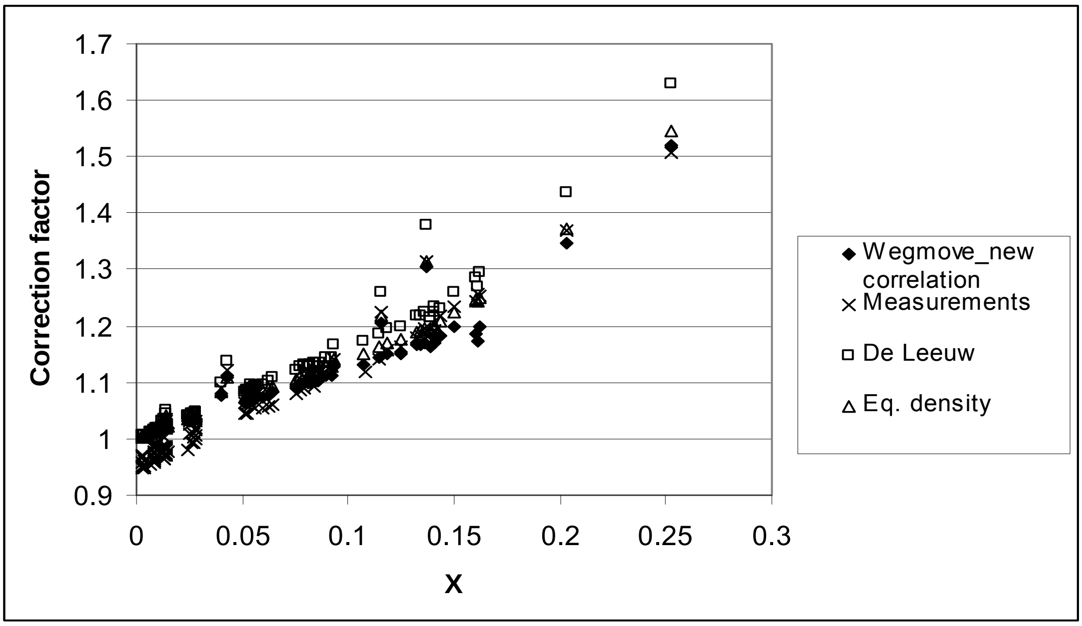

Fig. 9: Comparison of the results obtained by different calculations, for the high pressure tests

7 CONCLUSIONS

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

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

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

ACKNOWLEDGEMENTS

The authors thank MPM company which has provided some of the experimental data used for the validation of the WEGMOVE© code.

NOTATIONS

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

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