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RECENT OPERATOR INITIATIVES TO IMPROVE THE PERFORMANCES OF WET GAS FLOW MEASUREMENTS BY CONSIDERING THE LIQUID ATOMIZATION IN VENTURI FLOWMETERS

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1. INTRODUCTION

In gas chains comprising production, transport, storage & supply, natural gas as well as other gases are not always dry which means they are associated with liquid resulting from condensation as well as entrainments due to process for instance.

Such situation has conducted flow metering systems manufacturers, flow labs, standardization bodies [1] & operators [2] with the support of R&D to develop knowhow and wet gas measurement solutions since many years.

In oil & gas upstream area, the focus has been up to now the improvement of so-called wet gas flow meters WGFM as per ISO TR [3] especially for monitoring & metering of gas & gas condensate wells (gas with condensate & water entrainments) with significant results & progress both in hardware as well as in associated calculation & correction softwares.

In the energy transition period with an anticipated growth on natural gas as well as non-hydrocarbon gases, need for cost effective & accurate wet gas measurement is still expected.

The measuring strategy deployed by TotalEnergies together with ONERA to improve wet gas metering has consisted in understanding the flow physics [4] within measuring devices as well as developing flow models (WEGMOVE© & WETCALC©[1]) usable to predict wet gas flow behavior in Venturi & correct flow meters.

This strategy offers an efficient and added value approach for the design & operation of venturi based wet gas metering solutions in complex 3 phase wet gas flows conditions by providing physical & scalable corrections models as well as simulation tools for wet gas meter surveillance and validation.

[1] *WEGMOVE and WETCALC are two versions of a same flow model which differ from each other by the inlet condition imposed. In the WEGMOVE code, the fluid properties at actual flow conditions, the differential pressure ∆P, the Gas volume Fraction (GVF) and the Water in Liquid Ratio (WLR) are imposed. The WETCALC code uses information provided by an industrial Wet Gas Flowmeter (P, T, DP, Liquid hold up at the Venturi throat, WLR). The fluid properties at actual flow conditions are calculated from thermodynamic laws given through polynomial functions depending on both the actual pressure and the temperature. The Gas Volume Fraction is determined from an iterative algorithm.*

For Venturi flow meter correction for instance, there are several algorithms & equations to estimate the over-reading and compute the correct flowrates for the different phases using correlation but there are valid for specific range of conditions and they don't fully consider in detail flow morphology (films; droplets …) as well as liquid compositions like Water Liquid Ratio & properties.

This paper is describing the approach followed by TotalEnergies and ONERA to calculate & correct over-reading using flow modelling by presenting some industrial flow loop results of WEGMOVE correction code at different pressure and last R&D initiatives deployed to characterize oil & water droplet behavior & atomization process of the thin oil/water film inside the Venturi.

Basically, paper is developing experiments & results obtained in the wet gas flow loop at ONERA at different operating conditions using visualizations with high-speed camera & Laser Doppler techniques. It is also discussing as a conclusion future steps for WEGMOVE©& WETCALC© physical codes development & deployment.

2. WEGMOVE CODE AND ITS PERFORMANCES

Wet gas flows refer to flows with a GVF (Gas Volume Fraction) that is higher than 95%. The main flow regime encountered are mainly of the dispersed annular type, which means that in the center of the pipe, a mist of fine liquid droplets transported by the gas, flows at high velocity and that, along the wall of the pipe, a thin liquid film flows at low speed. Venturi flowmeters are widely used to measure the flowrates for wet gas flows because they are robust, and cost-effective. One of the main drawback of this technology is an over-estimation of the gas flowrate, generally called "over-reading", due to an increase in the differential pressure measured between the upstream and throat pressure taps, caused by the presence of the liquids in gas flow. This over-reading must be reduced for economic but also technical point of view.

2.1. Empirical correlations

Empirical correlations are providing a solution to reduce this over-reading but there are valid for specific range of operating conditions, which means that, when we are far from these conditions, the accuracy of the correlation is significantly reduced. The following table is summarizing the most widely used correlations.

Name of the correlation	Formula	Test Range
Equivalent Density Correction	$\Phi_g = \sqrt{1 + CX_{LM} + X_{LM}^2}$ with $C=\left(\frac{\rho_g}{\rho_l}\right)^n + \left(\frac{\rho_l}{\rho_g}\right)^n$ et n=0.5	
de Leeuw [4]	$\Phi_g = \sqrt{1 + CX_{LM} + X_{LM}^2}$ with $C=\left(\frac{\rho_g}{\rho_l}\right)^n + \left(\frac{\rho_l}{\rho_g}\right)^n$ $0.5 \le Frg \le 1.5$ n vaut 0.41 $Frg \ge 1.5$ $n=0.606(1-e^{-0.746Fr_g})$	β=0.4 1.5≤P(MPa) ≤9.8 0.5≤Frg≤4.8 $0 \le X_{LM} \le 0.34$
ISO TR/11583 [5]	$\Phi_g = \sqrt{1 + C.X + X^2}$ $C = (\frac{\rho_l}{\rho_g})^n + (\frac{\rho_g}{\rho_l})^n$ $n = \max(0.583 - 0.18\beta^2 - 0.578e^{-0.8Fr_{gas}/H}, 0.392 - 0.18\beta^2)$	0.4≤ β≤0.75 $0 \le X_{LM} \le 0.3$
Chisholm [6]	$\Phi_g = \sqrt{1 + CX_{LM} + X_{LM}^2}$ with $C=\left(\frac{\rho_g}{\rho_l}\right)^n + \left(\frac{\rho_l}{\rho_g}\right)^n$ et n=0.25	1≤P(MPa) ≤7 0.186≤β≤0.49 $0.5 \le X_{LM} \le 5$

2.2. WEGMOVE modelling

To predict the correction factor, a different approach is used by TotalEnergies and ONERA since few years. A flow modelling method has been developed [7] [8] [4] [9].

For that, the Venturi is divided in two regions: the throat and the convergent section. In parallel, the flow is divided in three entities: the gas and the droplets flowing in the central part of the pipe and the liquid film moving on the pipe wall. Balance equations are established for each zone of the Venturi, which means that mass and momentum conservations equations are applied for each flow entity.

The model supposes that there is no mass exchange in the meter between the gas and the liquid phase (evaporation, condensation), and in the convergent area it supposes that there is no mass transfer between the film and the droplets. On the contrary, an atomization of the liquid film is taken into account at the convergent/throat junction.

Boundary conditions at the inlet of the convergent section concern the velocities of the gas and the droplets, the liquid distribution between the droplets flow and the wall liquid film, and the droplets sizes. The gas velocity is fixed by the gas volume flow rate and the gas area. No slip is considered between the droplets and the gas flow. The initial film thickness is defined from a annular flow calculation taking into account the shear layer constrains exerted by the gas on the film, the liquid viscosity and the gravity force.

The volume of the liquid atomized at the end of the convergent section is deduced from a correlation developed by Salque [10] but only for air/water or air/oil flow. The size of the droplets issued from this atomization is calculated from the Azzopardi correlation [11]. The velocity of the initial droplets is considered as equal to the average liquid film velocity at the end of the convergent section.

The inlet liquid distribution, the volume flux of liquid atomized, the sizes of the droplets issued from the upstream flow or from the liquid film atomization inside of the Venturi meter, depend greatly on the gas/liquid surface tension, the gas and liquid densities and indirectly on the liquid viscosity through the liquid film thickness. Their values, in particular in gas/oil/water flows have a great influence on the prediction accuracy obtained by the flow modelling.

In the code, the oil/water mixture is considered as a unique fluid with its own physical parameters. The water/oil mixture properties are depending on the volume fraction of the water in the liquid phase, also called Water in Liquid Ratio, but also on the inversion phenomena. Developing accurate models for the mixture viscosity, mixture density, and mixture surface tension is of prior importance.

The definition of the density is obvious:

$$\rho_m = \lambda_w \ \rho_{water} + (1 - \lambda_w) \ \rho_{oil}$$

where ρ_m is the density of the mixture, λ_w is the Water in Liquid Ratio.

For the mixture viscosity, the relation used in the code is the one made by Pan [12] :

$$\mu_m = (1 - C_m)[(1 - \lambda_w)\mu_o + \lambda_w \mu_w] + C_m . \mu_{cont}(1 - \lambda_{dis})^{-2.5}$$

$$C_m = 1 - \exp\left(\frac{-Re3P}{K}\right) \ ; \ Re_{3P} = \frac{\dot{m}DUm}{Vs,g.\mu g + Vs,o.\mu o + Vs,w.\mu w}$$

Re_{3P} is the three phase Reynolds number, $\dot{m}$ is the superficial mass flux ($kg.m^{-2}.s^{-1}$), U_m is the overall superficial velocity ($U_m = j_g + j_o + j_w$). During his experiments, Pan fixed the parameter K equal to 15000.

To determine the viscosity, the localization of the inversion point must be computed to determine the continuous and dispersed phases of liquid mixture. This critical value of water in liquid ratio $\lambda_{w,inv}$ was determined from the Odozi correlation [13]:

$$\lambda_{w,inv} = 0.3372 j_g^{\ 0.2219}$$

Concerning the surface tension of the liquid, no correlation was found in the literature. So it was considered that the surface tension of the liquid is equal to the surface tension of the continuous phase.

$$\lambda_w \leq \lambda_{w,inv} \Rightarrow \sigma = \sigma_o$$

$$\lambda_w > \lambda_{w,inv} \Rightarrow \sigma = \sigma_w$$

2.3. WEGMOVE code performances against empirical correlations

The performances of WEGMOVE code have been tested and compared to empirical correlation results (De Leeuw, ISO, Equivalent Density Correction).

The experiments were conducted in a Venturi meter in three different configurations: horizontal (1), vertical (2), and vertical with straight section before the second pressure tap (3). The tests were carried out for 4 different pressures: 7, 12, 22, 30bars.

To understand whether the position of the tap is important or not for the estimation of the over-reading, the evolution of the over-reading as a function of the Lockhart-Martinelli has been drew for the two vertical configurations.

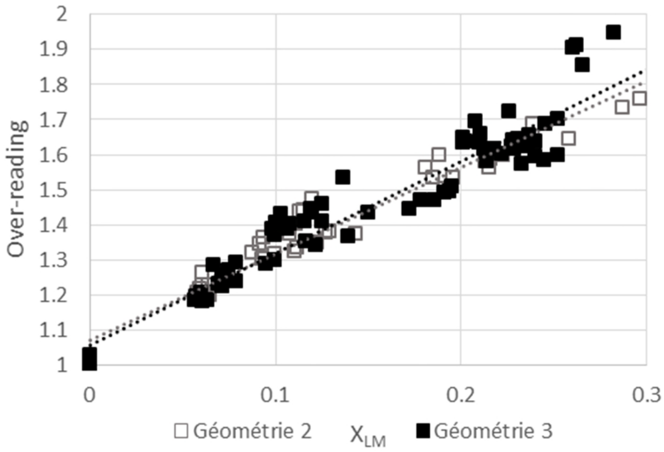


Figure 1 : Evolution of the over-reading as a function of the Lockhart-Martinelli parameter for different configurations

For the two geometries, the over-reading evolution is linear with the Lockhart-Martinelli parameter. The results are really close for the two configurations especially for X_{LM} lower to 0.12. Beyond this point, the over-reading is a bit higher for the third geometry.

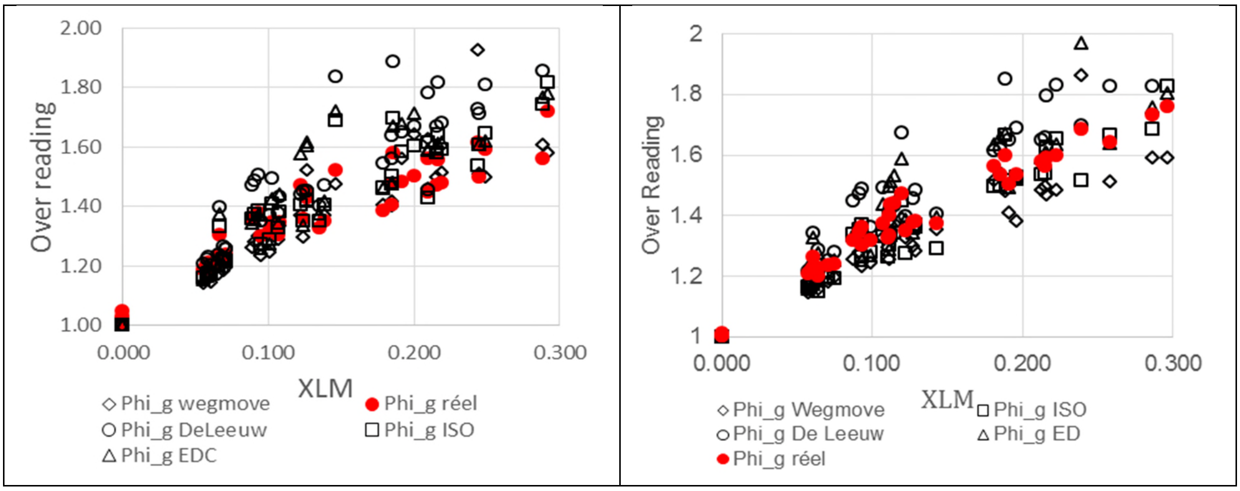


Figure 2 : Evolution of the over-reading as a function of X_{LM}, comparison of the performances of the correlations against WEGMOVE code. Left: Geometry 1, Right: Geometry 2

For small Lockhart-Martinelli parameters (<0.15), the over-reading computed by the different correlations and by WEGMOVE code are similar except for de Leeuw correlation that is over-estimating the over-reading for the two geometries.

For higher X_{LM}, for the vertical geometry, WEGMOVE code seems to underestimate the over-reading, while de Leeuw correlation is overestimating the over-reading. For higher X_{LM} parameter, the results are scattered.

To conclude this section, for low X_{LM} the correlations and the WEGMOVE code are giving good results, the over reading computed by the correlations and by WEGMOVE code tend to be close, but for higher X_{LM} there is big differences between the results provided by the correlations and the real over-reading.

Those results highlight the needs to improve the models under WEGMOVE code to increase the accuracy in estimating the correction factor. For that, several points have been identified to be improved. The models concerning the mixture viscosity and the localization of the inversion point must be improved, the definition of the mixture surface tension must be studied deeply, and the atomization process and the characteristics of the droplets must be considered in the models under WEGMOVE.

3. EXPERIMENTAL METHODS

3.1. ONERA test setup

The aim of this new study was to improve the modelling of the oil/water liquid film atomization observed at the end of the convergent section. For this, two main pieces of information are needed: the amount of liquid atomized and the mean size of the resulting droplets. This second parameter is generally obtained from optical techniques whose use requires an optical access that is difficult to achieve with cylindrical pipes. In order to be able to carry out these measurements, the choice was thus to represent the real phenomena observed on a Venturi flowmeter by a 2D plane geometry facilitating the use of the tools of characterization of the mists necessary to this study.

The experimental setup consists in a 194 mm long square pipe (46 x 46 mm^2) followed by a 2D convergent section (Figure 3). This section is formed by two opposite flat plates inclined respectively at 10.5° and 20° to reproduce the angle of the convergent and the pipe area reduction imposed by the application of the Venturi ISO standard. This 2D convergent is followed by a single flat plate placed at the end of the convergent wall inclined at 10.5°. This plate represents the throat section wall of a real axisymmetric Venturi flowmeter. This test section was placed downstream of a plenum chamber followed by a square convergent used to reduce the air turbulence and control the air velocity distribution at the inlet of the square pipe. The liquid phase was injected 101 mm upstream of the inlet of the convergent section through a rectangular slot.

This setup was installed on the ONERA multiphase test flow loop which enables to generate air-water-oil flows at atmospheric pressure. The test section is placed in a vertical downward configuration. Finavestan oil A50B used previously by Salque *et al* was used [10]. Before their injection in the test section, the water and the oil were mixed with a static mixer to form an emulsion. An air/liquid separator followed by a water/oil separator are used to recover the liquid first and then the oil. Four air flowrates and five liquid flowrates were considered (31g/s, 40 g/s, 49g/s and 58g/s and 16 l/h, 31 l/h, 45 l/h, 60 l/h, and 76 l/h respectively). The corresponding superficial velocities are 36, 46, 54 and 64 m/s for the air flow and 0.007, 0.013, 0.018, 0.024 and 0.031 m/s for the liquid flow. Five WLR were considered (0; 0.2; 0.4; 0.6 and 1).

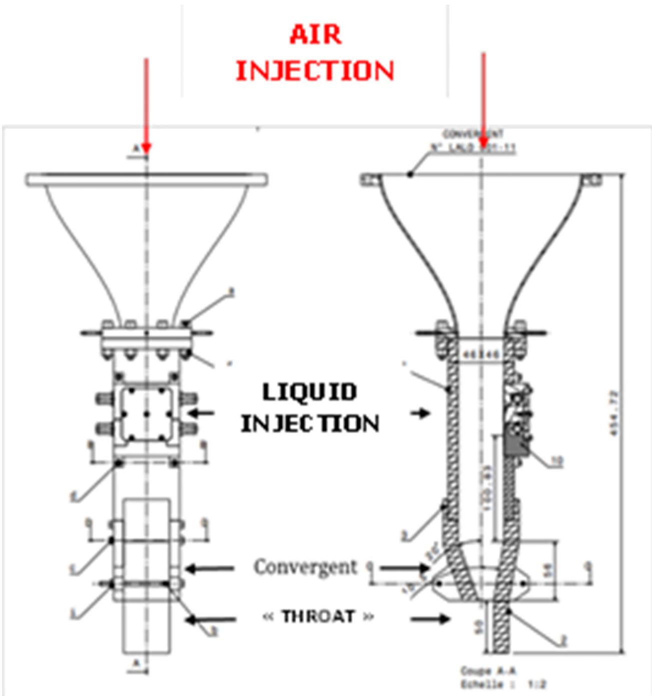


Figure 3 : Experimental test section

3.2. High speed visualizations

During the test, the influence of the flow conditions on the liquid film structure and its atomization were analyzed through high-speed flow visualizations. The images were acquired with a Phantom v341 video camera. Two types of visualization were considered (front and side views). In the first case, the film structure and the atomization process are obtained. The second configuration gives information about the film thickness and the atomization location.

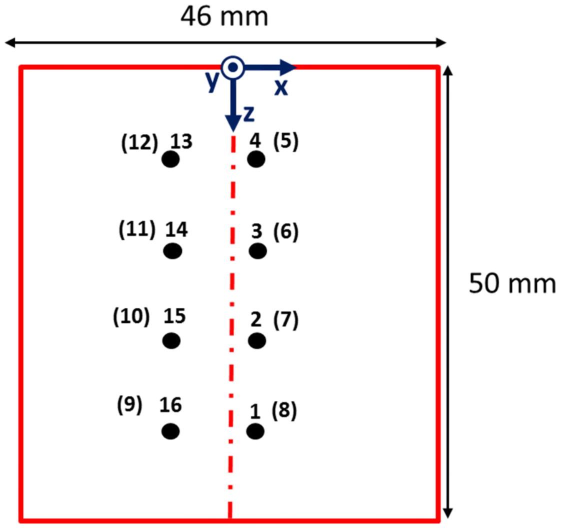
3.3. Droplet size and velocity measurements

Droplet size and velocity measurements obtained at different locations downstream of the convergent outlet (Figure 4) are used to analyze the droplet spray issued from the atomization of the liquid film.

These measurements were obtained using the phase Doppler anemometry technique. This method is based on the Mie diffusion of laser light by spherical particles. It principle is as follows: the intersection of the two laser beams issued from a same laser creates a fringe network inside of probe volume. When a particle moves inside of this probe volume, it scatters light in all directions through Mie scattering process. This light is then recorded by different photodetectors placed in different locations around the probe volume. The photodetectors provide electrical signals (called bursts) whose frequency is linked to the fringe distance and the particle velocity. The phase shift measured between two photodetector signals is related to the diameter of the particles.

The experiments were performed with a PDA Dantec system. Only one component of the velocity was recorded (U_z). On a given point and for each flow condition, the probability density function (p.d.f.) of the droplet size and velocity distribution can be calculated and averaged values can be deduced. From the droplet size distribution, the Sauter mean diameter D_{32}, which is relevant for the modelling of the gas/droplet mass, momentum or heat exchanges, is computed:

$$D_{32} = \frac{\sum_{i=1}^{N} d_i^3}{\sum_{i=1}^{N} d_i^2}$$



Point	x[mm]	y [mm]	z [mm]
1	3	4	40
2	3	4	30
3	3	4	20
4	3	4	10
5	3	5	10
6	3	5	20
7	3	5	30
8	3	5	40
9	-7	4	40
10	-7	4	30
11	-7	4	20
12	-7	4	10
13	-7	5	10
14	-7	5	20
15	-7	5	30
16	-7	5	40

Figure 4: PDA locations used during the experiments

4. MULTIPHASE FLOW VISUALIZATIONS WITH HIGH-SPEED CAMERA

To understand the flow phenomena occurring inside the Venturi, flow visualizations were performed with the use of a high-speed camera. The aim was to understand the atomization process of the thin film and identify the flow condition required for.

4.1. Air-water flows

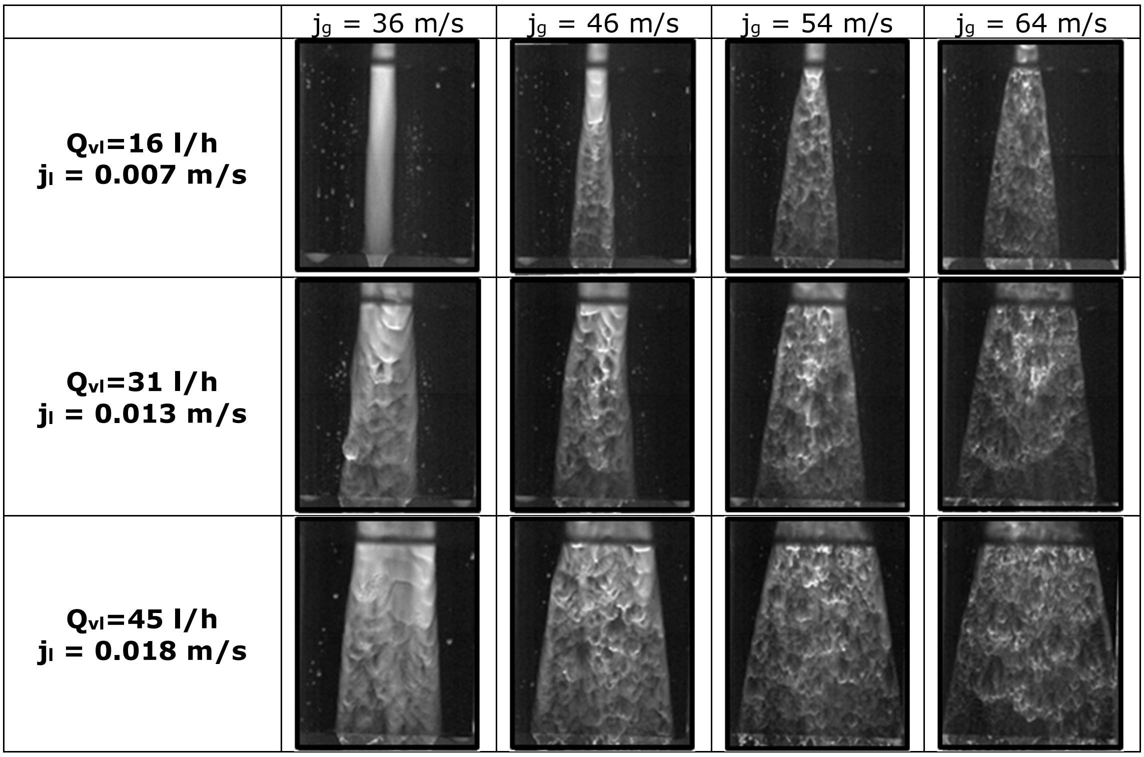
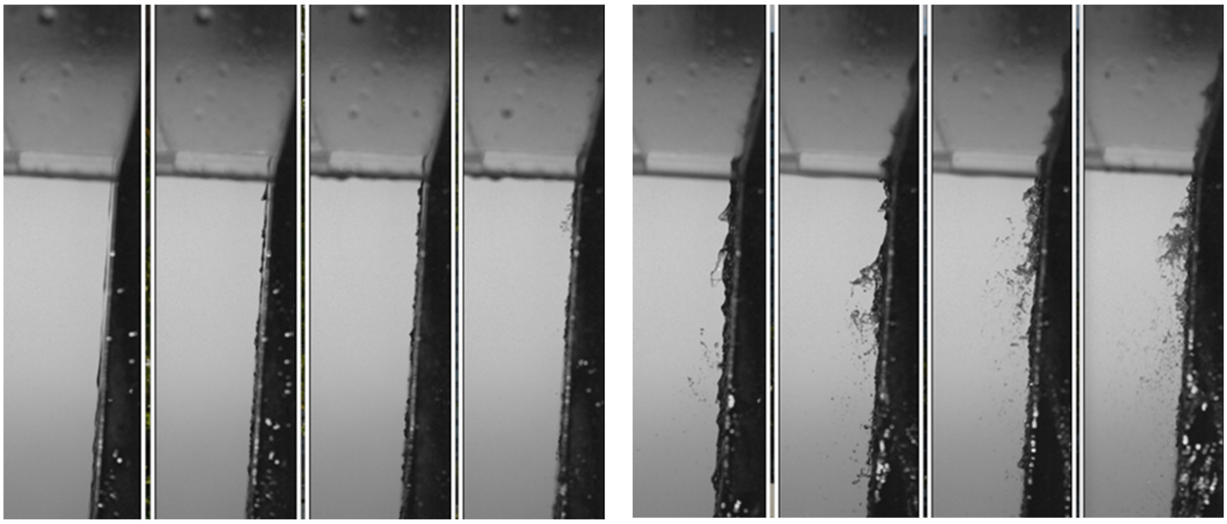


Figure 5 : Evolution of the film spreading depending on the air and water flowrates

In Figure 5 the liquid film area on the downstream plate simulating the throat section of a Venturi meter is presented. The spread of the liquid film increases with both the air velocity and the liquid flowrate. At the air/film interface, waves appear which are transported from the upstream to the downstream direction. Their frequency and velocity increase with the air velocity.



36 m/s 46 m/s 54 m/s 64 m/s 36 m/s 46 m/s 54 m/s 64 m/s

WATER 31 l/h WATER 76l/h

Figure 6 : Side views of the air water flow.

Figure 6 highlights the strong influence of liquid and air flow rates on the onset of the atomization process. For large liquid flow rates (such as 76 l/h), the atomization process is important. Ligaments are first stretched on the surface of the waves under the action of air shearing until they are torn off to form liquid clusters. These clusters are then atomized to create fine droplets. Atomization process and its beginning as a function of operating conditions (air and water flowrates) have been studied too [Figure 7].

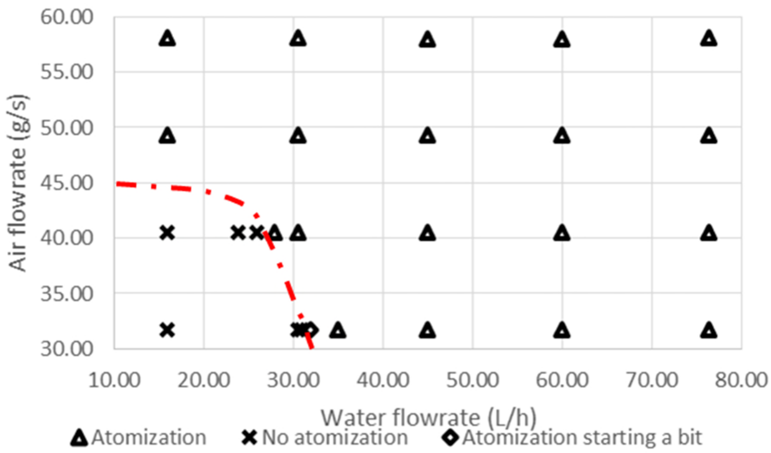
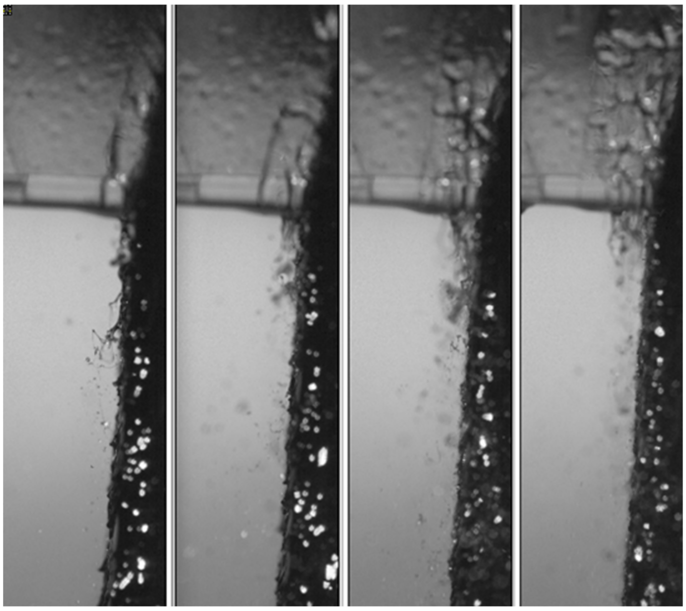


Figure 7: Identification of the beginning of the atomization process for air/water flow

For an air flow rate of 32 g/s, the onset of the atomization phenomenon occurs at a water flow rate between 32 l/h and 35 l/h. For a 40 g/s air flowrate, the atomization process appears at a water flowrate between 26 and 28 l/h. The critical water flow rate corresponding to the start of the atomization process decreases as the air velocity increases.

4.2. Air-oil flows

For air-oil flows, even for the lowest air and oil flowrates (32 g/s and 16 l/h), the atomization process is observed. In the convergent section located upstream of the downstream plate simulating the throat section of a Venturi meter, the liquid film spreads both over the entire 10.5° inclined wall and slightly up the two adjacent lateral walls. As observed for the air/water case, waves on the oil/air interface are atomized under the air shearing effect. This is illustrated in the Figure 8



36 m/s 46 m/s 54 m/s 64 m/s

Figure 8: Visualization of the air-oil flow for a liquid flowrate equal to 45L/h and air superficial velocities

4.3. Air-oil-water flows

Air-water-oil flows were also studied. For an air superficial velocity equal to 36 m/s, the following water liquid ratios were tested: 0/0.2/0.4/0.6/1. Figure 9 summarizes the visualizations. For a WLR (Water in Liquid Ratio) λ equal to 0, the wave amplitude is low and small ligaments are broken. As observed in the previous paragraph, for this WLR, in upstream convergent section, the liquid film spreads not only on the entire wall inclined at 10.5° but also slightly on the two neighboring walls. This phenomenon is also observed for a WLR equal to 0.2. For a WLR of 0.4, the liquid spreading on the lateral walls is no more observed. The amplitudes of the waves issued from the upstream flow are larger compared to the two previous WLR. For a WLR equal to 0.6, the atomization rate observed is more important compared to the previous WLR. At contrary, for a WLR equal to 1, the wave amplitude is smaller and no atomization phenomenon is observed.

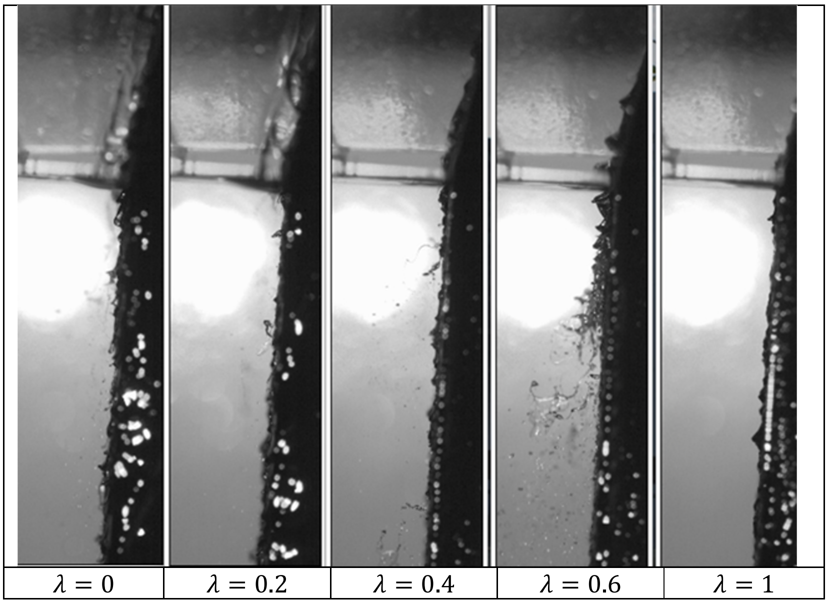


Figure 9: Lateral visualizations of the liquid film for an air flowrate equal to 32g/s

5. CHARACTERIZATION OF THE ATOMIZATION PROCESS WITH PDA TECHNOLOGY

In Figure 10 the longitudinal distribution of the water and oil mean size droplet is plotted for two air velocities. We observe a finer atomization of the oil liquid film compared to the water case. In addition, it is noted that the higher the air velocity, the smaller the droplet size. These observations result from the effect of the air to liquid surface tension and the air shearing effect at the liquid film interface. On the contrary, the liquid velocity seems to have a small effect on the droplet size (Figure 11).

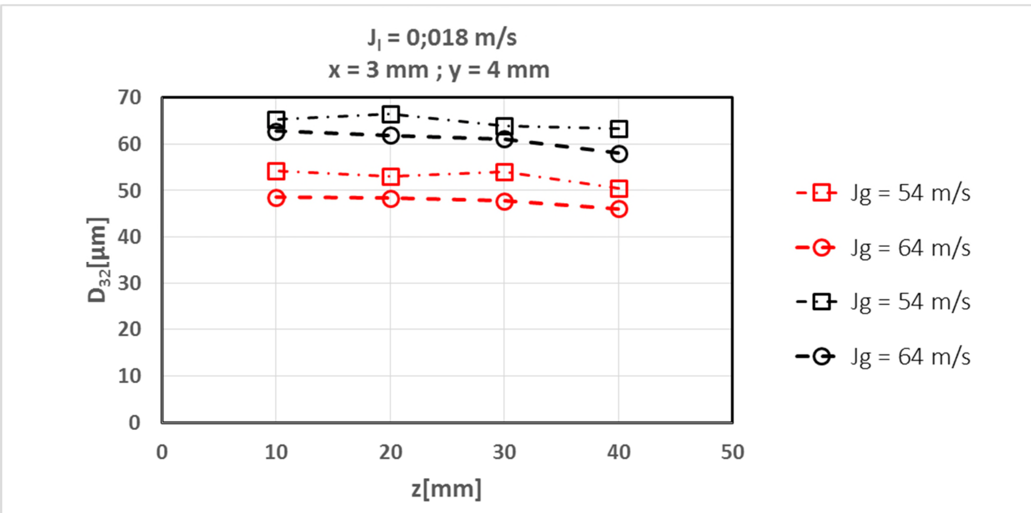


Figure 10: Influence of the air velocity on the droplet size (Black : water ; Red : Oil)

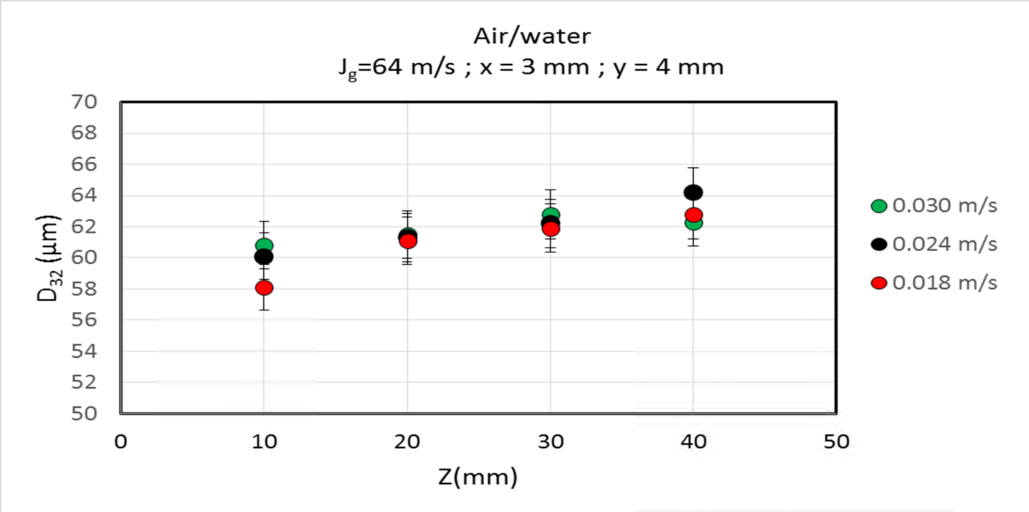


Figure 11: Influence of the liquid velocity ratio on the droplet size.

In Figure 12, the influence of the droplet size on their respective velocity for different water in liquid ratio is analyzed. It is obvious that the smaller the droplet, the faster they are accelerated by the gas flow. No influence of the water in liquid ratio is observed. On the contrary, this parameter influences greatly the mean droplet size as shown in Figure 13. For the two air velocities tested, a linear relationship is obtained between the mean droplet size and the water in liquid ratio. The interpretation of this result is not obvious. It seems that the atomization of a water/oil emulsion behaves like a mixture with separate phases where each interface would be sheared by the same gas flow producing two separate probability density functions whose number of droplets would be proportional to the respective flow rate of the considered phase. This interpretation is significantly different from an emulsion formed by a dispersed phase within a dominant liquid sheared by an external gas flow. In the WEGMOVE modelling, the mean droplet size depends on the liquid density and surface tension [7].

$$D_{32} = \lambda_T \frac{15.4}{We^{0.58}} \text{ with } \lambda_T = \sqrt{\frac{\sigma}{\rho_l g}} \text{ and } We = \frac{\rho_l j_g^2 \lambda_T}{\sigma}$$

In consequence, the mean droplet size is proportional to $(\sigma/\rho_l)^{0.79}/j_g^{1.16}$. The surface tension is that of the dominant phase and the liquid density increases linearly with the water in liquid ratio. This means that, for a same dominant phase, the size of the droplets decreases with the increase of the density linked to the increase of the water in liquid ratio. This influence predicted by the model does not correspond to the experimental observation presented above. A new model is therefore needed to improve the accuracy of the model.

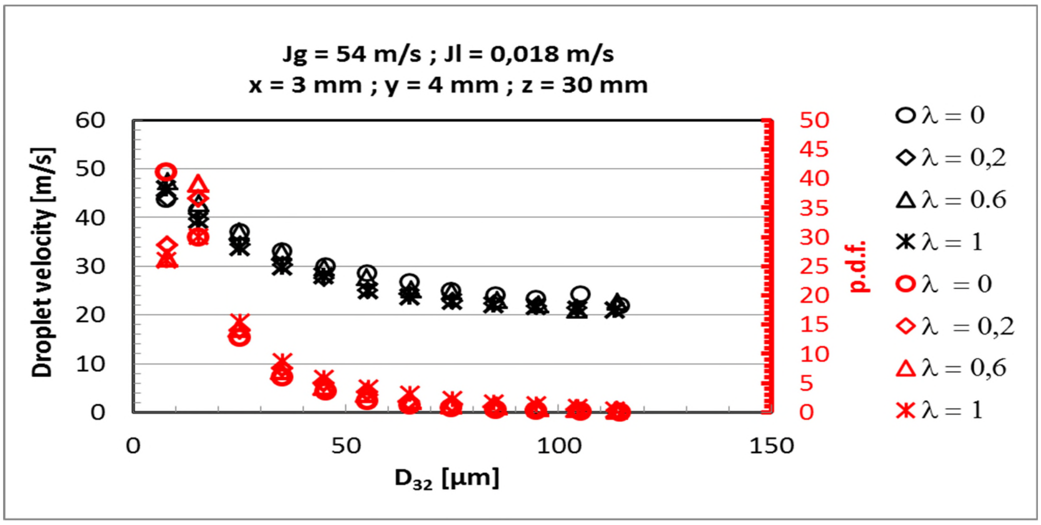


Figure 12: Influence of the droplet size on the droplet velocity for different WLR. (Black: Droplet velocity; Red: Droplet size probability density function)

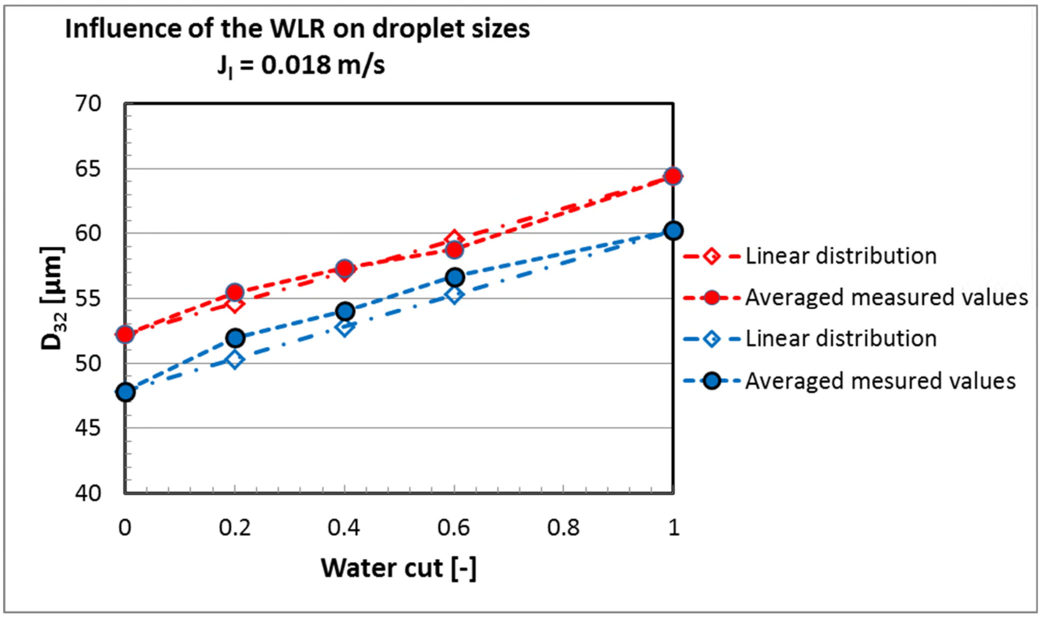


Figure 13: Influence of the WLR on the droplet size

6. CONCLUSION

For wet gas metering, two different approaches can be used to correct the over-reading and improve measurement accuracy: correlations or flow modelling. The flow modelling approach has been developed by TotalEnergies and ONERA since few years to provide an alternative to empirical correlations widely used but only valid for specific range of operating conditions. This approach with associated physical models which consists in considering all the flow phenomena occurring inside the measuring devices like Venturi have been implemented under in-house code. Such codes are usable either for laboratory applications (WEGMOVE) or field applications (WETCALC) using differential pressure and liquid content as inputs.

Recent flow loop tests as well as laboratory experiments have shown the importance of parameters such as the liquid mixture viscosity, the surface tension, and the water in liquid ratio where the inversion phenomena occur.

Flow visualizations as well as droplet characterization at the end of the convergent section thanks to the PDA technology, have shown the complexity of flow morphology in measuring devices and particularly the atomization process of two-phase films that significantly contributes to the over-reading.

The experimental results lead us to several observations, in particular, a threshold condition depending on the air velocity and liquid flowrate permitting the atomization of the liquid film. Furthermore, a linear relationship between the water in liquid ratio and the droplet size is obtained. All observations made through the going R&D program also indicate that the inversion phase localization must be improved for 3 phase wet gas metering models.

This work indicates that the complexity of wet gas phenomena in meters must be addressed in the future with a focus on the modelling of water/oil properties and their impact on the atomization process. Consequently, it is anticipated that simple correlation-based solution will not be suitable to reach high gas accuracy results on high pressure measurements. Any further initiative to improve accuracy of wet gas metering and to get suitable information for that will require to develop and deploy physical modelling approach as started by TotalEnergies with ONERA support.

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