

Lessons from wet gas flow metering systems using differential measurements devices: Testing and flow modelling results

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Abstract:

A significant number of wet gas meters used for high GVF & very high GVF are based on differential pressure measurements. Recent high pressure tests performed on a variety of different DP devices on different flow loops are presented. Application of existing correlations is discussed for several DP devices including Venturi meters. For Venturi meters, deviations vary from 9% when using the Murdock correlation to less than 3 % with physical based models. The use of ΔP system in a large domain of conditions (Water Liquid Ratio) especially for liquid estimation will require information on the WLR

This obviously raises the question of the gas and liquid flow metering accuracy in wet gas meters and highlight needs to understand ΔP systems behaviour in wet gas flows (annular / mist / annular mist).

As an example, experimental results obtained on the influence of liquid film characteristics on a Venturi meter are presented. Visualizations of the film upstream and inside the Venturi meter are shown. They are completed by film characterization. The ΔP measurements indicate that for a same Lockhart Martinelli parameter, the characteristics of the two phase flow have a major influence on the correlation coefficient. A 1D model is defined and the results are compared with the experiments. These results indicate that the flow regime influences the ΔP measurements and that a better modelling of the flow phenomena is needed even for allocation purposes.

Based on that, lessons and way forward in wet gas metering systems improvement for allocation & well metering are discussed and proposed

1 INTRODUCTION

In addition to “conventional“ multiphase applications, the oil & gas industry has to cope with an increasing number of applications for metering systems usable in wet gas range which corresponds to the upper end of multiphase GVF range i.e. $95\% < \text{GVF} < 100\%$ for :

- Reservoir monitoring on individual wells or in place of test separators
- Allocation on individual wells or flow lines
- Production optimisation

Expected capability of such wet gas meters are ranging from high accurate gas measurements to true 3 phase wet gas meters able to give gas, water & condensate in wet gas conditions

If manufacturers are now proposing several options to measure liquid and gas, gas and water or three phases, proposed technology and related performances (operating envelope, accuracy) still have some limitations in the wet gas range .

As an example, most of the wet gas meters used for very high GVF are based on differential pressure measurements using Venturi and other differential pressure geometries.

In order to better assess performance and identify ways of improvement , TOTAL and GDF have entered into a number of testing and R&D programs addressing differential pressure systems behaviour (Venturi & V cone based) both in low & high pressure conditions.

On one side this paper describes results obtained with Venturi based wet gas meters in HP & LP conditions and discusses application of published models & correlations.

On the other side, it describes some results obtained on Venturi behaviour modelling in wet gas flows (annular / mist / annular mist).

Results obtained on various flow loops and basic research are pointing out the question of the gas and liquid flow metering accuracy, highlighting difficulty to implement wet gas meters and to apply flow loop results to real cases by maintaining accuracy.

For confidentiality reasons, system and flow loop references are not published.

2 THE FLOW LOOPS

In the last years, TOTAL and GDF were involved in some flow loop tests. During these experiments, various thermodynamic and flow conditions were tested, with varying fluids, meter installation - horizontal or vertical, presence of a mixer or not - from one loop to another.

Some tests were performed under low pressure conditions (less than 7 bars), notably at the ONERA loop in France, and others under high pressure conditions (until 250 bars).

Testing loops use combination of fluids which range from air and water to real hydrocarbons. Tests were performed in two phase or 3 phase flow conditions.

Baker’s vertical and horizontal maps have been used to represent the expected flow regimes types. *Figure 1* and *Figure 2* illustrate the variety of regimes that one can encounter and it show that the regimes during these tests might have been mainly annular and dispersed annular.

In most of the tests, as flow patterns visualisation devices were not installed, flow regime prediction studies were also conducted in some cases using flow simulators like OLGA for instance. Prediction models are built using experimental data and as a consequence their accuracy is greatly dependent on the conditions of the experiments runs (pipe diameter, orientation, fluids, thermodynamics...).

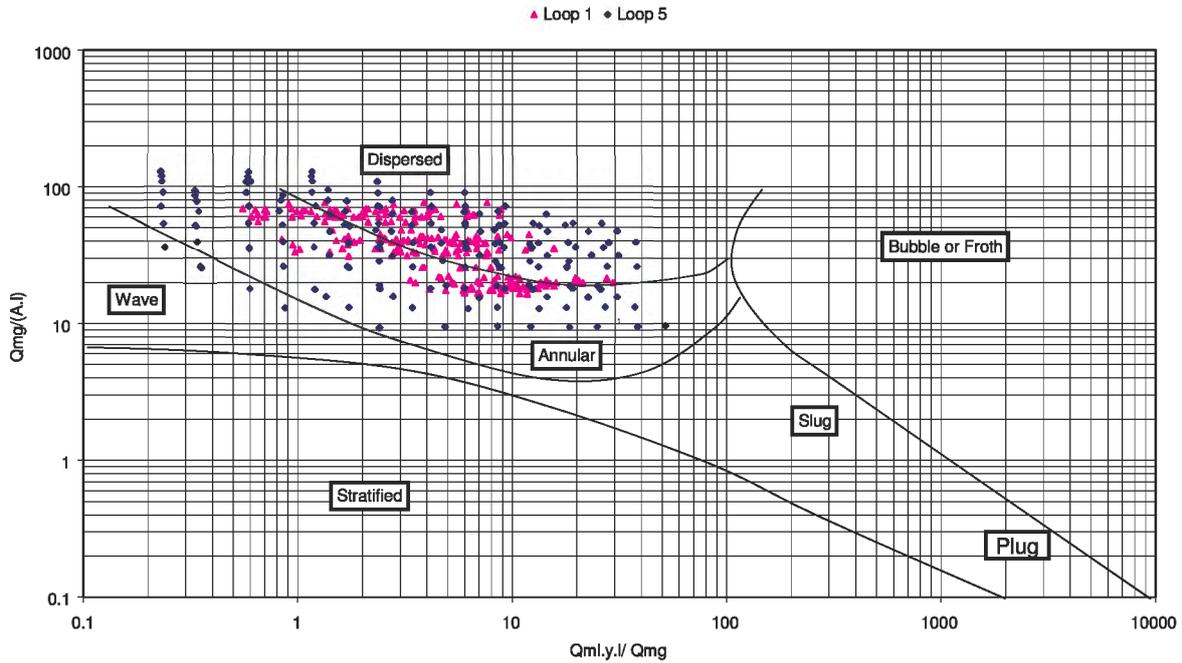


Figure 1 : Loop tests points displayed in the Baker Map – horizontal

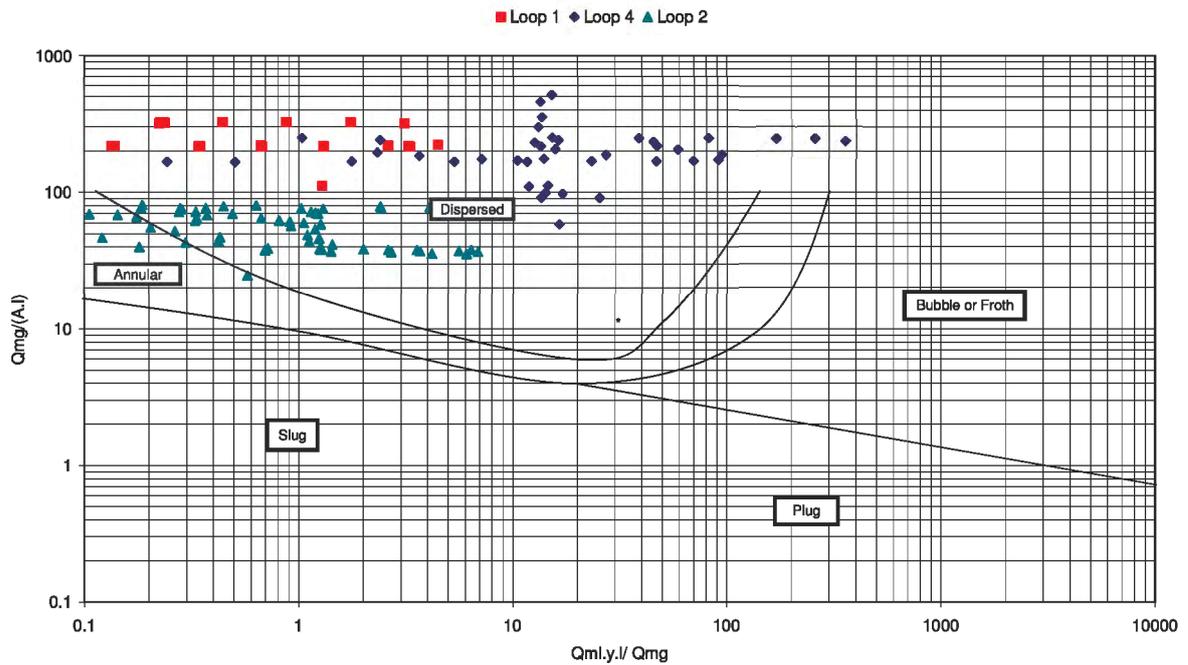


Figure 2 : Loop tests points displayed in the Baker Map - vertical

3 VENTURI BASED WET GAS METER SYSTEMS

3.1 Industrial status

Most of the wet gas meters of the market are using Venturi geometries, alone or in combination with other devices.

If total flow rates are generally derived from a differential pressure measurement across a Venturi meter or a V cone, liquid fraction and water fraction are either measured from a second Δp measurement and / or from specific fraction measurements (gamma attenuation, microwave absorption...)

3.2 Venturi modelling

In principle, mass flow calculations using pressure drop measurements in a Venturi are straightforward as based on the Bernoulli's equation.

Such principles have been very successful in homogeneous flows but need to be corrected when liquid phase is present.

Three types of models and approaches can be applied: physical models, statistical models, and intermediate models between these two approaches.

The corrected equation for wet gas mass flow is then:

$$Qm_g = \frac{Y\sqrt{2\rho_g\Delta p}}{\Phi_g}$$

Where Qm_g , ρ_g , Δp and Y are respectively the gas mass flow rate, the gas density, the pressure drop along the device and a corrective coefficient depending on the device geometry, and accounting for the pressure loss and the compressibility of gas. Φ_g is the over-reading factor accounting for the presence of liquid and is the main topic of this section.

3.2.1 Statistical models

They are built on statistical processing of tests data. The obtained corrections are very sensitive to the conditions under which the equations were established. We can quote Murdock's and Steven's correlations [1]. The latest takes into account the gas Froude number and the Lockhart Martinelli parameter while Murdock only uses the Lockhart Martinelli parameter.

$$\text{Murdock: } \phi_g = 1 + 1.26X_{LM}$$

$$\text{Steven: } \phi_g = \frac{1 + AX_{LM} + BFr_g}{1 + CX_{LM} + DFr_g}$$

A, B, C, D are parameters depending on the ratio between gas and liquid densities. Fr_g and X_{LM} are the gas Froude and Lockhart Martinelli numbers.

The Lockhart Martinelli number equation is (the indexes g and l refer to gas and liquid):

$$X_{LM} = \frac{Qm_l}{Qm_g} \sqrt{\frac{\rho_g}{\rho_l}}$$

3.3 Simple physical model: the Equivalent Density Correction

Such a model is based on the calculation of an equivalent density of the a fluid flowing at the superficial velocity of the gas and given the same momentum flux in a pipe section than the two phase flow. It uses a slip factor K between the gas and the liquid phase $K = \frac{U_g}{U_l}$. It permits to deduce a Φ_g factor from the following expression

is:

$$\Phi_g^2 = 1 + CX_{LM} + X_{LM}^2$$

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

If the liquid flows as very small droplets, K equals 1 and one obtains an simplified expression called in this paper "droplets model-physical correction".

3.4 An intermediary approach between physics and statistics

3.4.1 It is the most commonly used approach, with the De Leeuw correction [2]/[3] :

$$\Phi_g^2 = 1 + CX_{IM} + X_{IM}^2$$

$$C = \left(\frac{\rho_l}{\rho_g} \right)^n + \left(\frac{\rho_g}{\rho_l} \right)^n$$

$$n = 0.606 \left(1 - e^{-0.746 Fr_g} \right) \text{ for } Fr_g \geq 1.5$$

$$n = 0.41 \text{ for } 0.5 \leq Fr_g \leq 1.5$$

4 VENTURI METER PERFORMANCE

4.1 Venturi performances for gas metering

The three types of correction were tested on the data from the different test loop programs and a summary of their accuracies in terms of mass flow rates prediction is given

4.1.1 Murdock's correction for Venturi

The Murdock's correction, being a very simplified correction, does not lead to very good accuracies as can be seen in *Table 1*. The errors on gas mass flow rates are of about +/-8% and even reach 103% at 6 bars.

Loops	1	2	3	4	5
β	0,5	0,6	0,65	0,6	0,6
ID	5"	2"	2"	5"	6"
6 b			103%		
15 b					9%
30 b					7%
45 b					6,5%
50 b		9%			
60 b					6.3%
100 b				+/-6%	
80=>240	1.3=>8.7%				

Table 1: Performances of the Murdock's correction on the test loops data

4.1.2 De Leeuw's correlation

The correlation fits well with the data with which it was created (Sintef) with an error of +/-2% on gas mass flow rate. However, it can be seen in *Table 2* that in other conditions, its accuracy varies with the tests pressures, with the beta parameter and the inner diameter. Notably, it shall not be used when pressure is low as the error on gas mass flow rates reaches +/-28% in the loop 3, at 6 bars. Apart from low pressure conditions, accuracy ranges from 3% to 6,4%.

Loops	Sintef	1	2	3	4	5
β	0,4	0,5	0,6	0,65	0,5	0,6
ID	4"	5"	2"	2"	5"	6"
6 b				+/-28%		
15 b	+/-2%					+/-5,5%
30 b	+/-2%					+/-4%
45 b						+/-4,5%
50 b			+/-3%			
60 b	+/-2%					+/-3,5%
90 b	+/-2%					
100 b					+/-6,4%	
80=>240		+/-5%				

Table 2: Performances of De Leeuw's correction on the test loops data

4.1.3 Droplets model - physical correction

The results displayed in the *Table 3* clearly show that the accuracy of the droplets model correction increases when pressure grows. This may be accounted for by a better atomization of the liquid film from the pipe wall when the pressure increases. This model can reach very good accuracy with $\pm 2.9\%$ errors at the loop 1 from 80 to 240 bars.

Loops	1	2	3	4	5
β	0,5	0,6	0,65	0,6	0,6
ID	5"	2"	2"	5"	6"
6 b			$\pm 45\%$		
15 b					$\pm 16\%$
30 b					$\pm 11\%$
45 b					± 9.5
50 b		$\pm 8,7\%$			
60 b					± 5.4
100 b				$\pm 3,4\%$	
80 \Rightarrow 240	$\pm 2.9\%$				

Table 3: Performances of the droplet model correction on the test loops data

4.1.4 Example of gas flow rates measurements curves

The curves below display some data points from the loops tests. The errors on gas mass flow rates are plotted against the Lockhart Martinelli parameter for the Murdock and De Leeuw correlations and for the droplet model correction. In *Figure 3* the data from the loop 5 corresponding to a gas Froude number of 1.39 are extracted at 60 bars, in *Figure 4* all the points from the loop 1 corresponding to a pressure of 80 bars are plotted.

In these conditions, the flow maps predict a misty regime and it can be seen that the droplets model is the best correction with an accuracy of $\pm 3\%$. The Murdock's and De Leeuw's correlations are less accurate with errors between 2% and 8%.

This indicates that when the flow regime is known, here the droplet regime, a physical approach is best suited to gas flow rates calculations than statistical correlations and leads to a good accuracy.

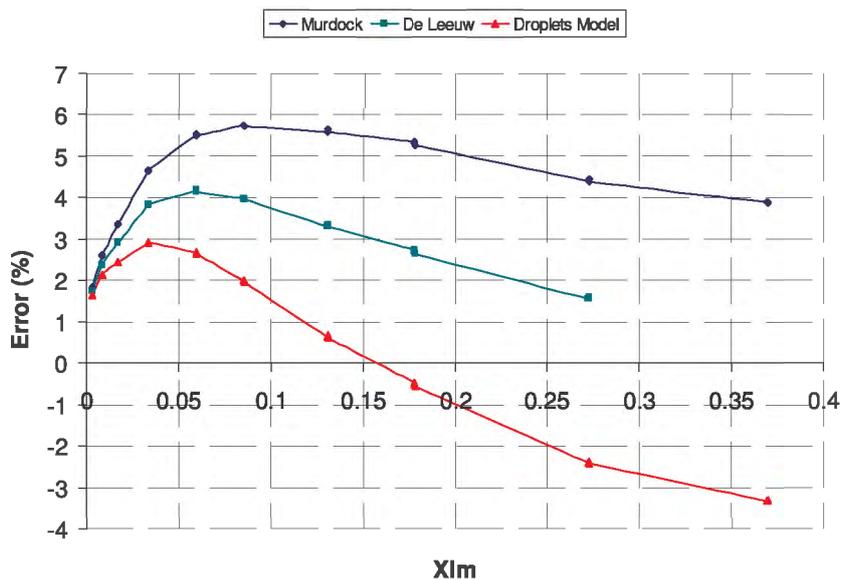


Figure 3 : Performances of the corrections at the loop 5, 60 bars, $Fr_g=1.39$

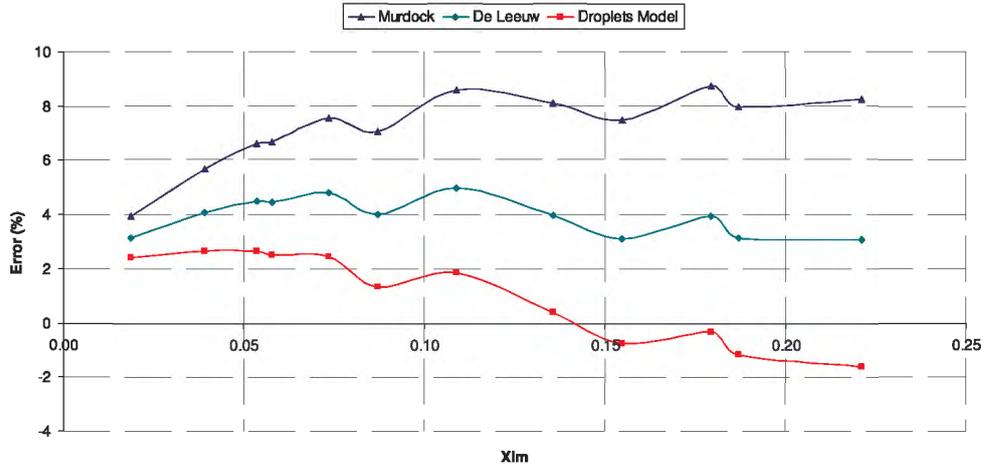


Figure 4 : Performances of the corrections at the loop 1, 80 bars

4.2 Liquid measurement using double Δp devices: 3 phase wet gas metering application

Operators needs concerning wet gas are the measurement of gas flows as well as of liquid flows. Besides, the correction of gas flow rates requires the knowledge of the liquid content of the flow. Therefore, it is of paramount importance to use an additional measurement device to enable the calculation of the liquid flow.

A strategy in use is to install a second pressure drop device to get more information. The new measured pressure drop could be of several types, between different locations: inlet and outlet of the Venturi, pressure drop measurement from different device ...

Different responses of the pressure drop devices will be required when liquid loading is varying so that information can be extracted to calculate liquid flow rates.

Moreover, the behaviour of each device must be well known to predict accurately the gas and liquid flow rates.

In this paper, we have tested such devices in three phases systems. Tests run under three phases conditions – gas and liquid hydrocarbons and water – showed that the water cut is playing an important role in the behaviour of the devices and consequently that behaviour in 3 phases could be significantly different from behaviour in 2 phases. In the *Figure 5*, displaying the difference between the two pressure drops measurements of a Δp system, a discontinuity can be seen when the water in liquid ratio meets the value of 60%. This value corresponds with the transition point between water continuous and oil continuous domains.

Consequently, to calculate the flow rates of gas and liquids in a large range of WLR, one must also know and measure the water cut.

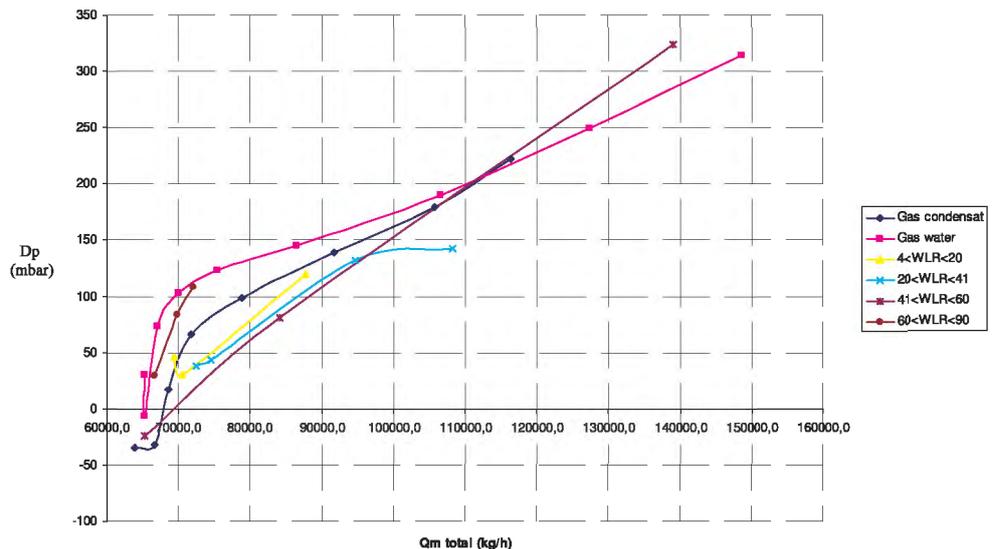


Figure 5 : Difference between the two measures of a Δp system

4.3 Conclusions and lessons

Most of correlations and models which are generally used to correct the Venturi meter gas mass flow rates according to the liquid loadings are mainly statistical and do not use accurate physical approaches. They present a great dispersion in the results and their performances vary as geometries and flow conditions vary. As a consequence, claimed accuracy of published correlations cannot be generalised / extrapolated and will not strictly apply without specific meter calibration.

On the other side, physical models based on flow morphology are very accurate when applicable; this is the case of droplets models applied to Venturi meter correction in mist flow. Such assumptions need to be extended to more complex flow regimes like annular & annular mist flows through a better understanding of fluids behaviour in Venturi. An example of this approach is presented in the following part of this paper.

Behaviour of Venturi and other ΔP systems in 3 phase wet gas conditions is obviously a new area which has to be considered in detail when establishing correction for liquid when 3 phases are present.

Points to be also considered when testing, interpreting and generalising flow loop tests concern both the flow regimes knowledge and prediction - annular, dispersed annular, stratified... - and the extrapolation of two phase results to three phases conditions - gas, liquid hydrocarbons, water.

5 DETAILED ANALYSIS OF THE FLOW PHENOMENA IN THE VENTURI METER AND THEIR REPERCUSSION ON ΔP MEASUREMENTS

As indicated previously, to improve the metering methods of wet gas, it is necessary to improve our knowledge of the basic phenomena which take place in the pipe, to model them and to deduce correction laws which take into account the characteristics of the two phase flow upstream of the flow meter. However, the knowledge of the characteristics of the two phase flows under real flow conditions, is difficult to reach (150 bars, 200°C) and the approach developed at ONERA consists of making a detailed study on the influence of various parameters under low pressure conditions, with air and water, in order to define those necessary to be measured in situ in order to ensure a significant improvement of the metering accuracy. Results presented in previous papers [4][5] showed that a law of correction must take into account the quantity of liquid in gas but also the distribution of this liquid flowing at the wall as a film and in the core region as droplets. This law must also take into account the size of these droplets. In this paper we will focus on the behaviour of the liquid film on the wall and its influence on the law of correction. From the experimental analysis a 1D model was developed. It will be compared to low pressure results in annular flow regime.

5.1 Experimental study

5.1.1 Experimental procedure

5.1.1.1 ONERA wet gas test facility

The wet gas tests were carried out at low pressure on the ONERA experimental flow loop (*Figure 6*). The gas flow (air) is generated by means of high pressure tanks. The gas flow rate up to 0.21 kg/s, is controlled by a sonic nozzle located upstream of the test section. The mass flow rate of liquid (water) can be varied from 0 to 0.1 kg/s. The liquid line is equipped with electromagnetic flow meters. This loop can be used from atmospheric pressure to 5 bars. A separator is used to recover the liquid.

The test section is placed in a vertical downwards orientation. It is composed of:

- a flow conditioner,
- a liquid film injector,
- a Venturi meter.

The pipe diameter ($D = 2.R$) is 100 mm. Two identical Venturi flow meters with a β of 0.6 were machined in steel for ΔP measurements and in Perpex for flow visualisations. The half angles of the upstream convergence and the downstream diffuser were respectively 10.5° and 7.5°.

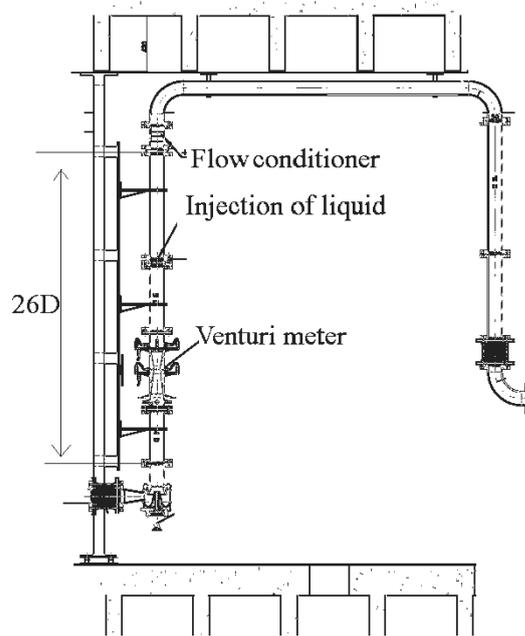


Figure 6 : Experimental test set-up

5.1.1.2 Experimental techniques used for analysing the film behaviour.

Two different techniques are used to analyse the film behaviour. In order to determine the entrainment phenomena through the Venturi meter, flow visualisations are performed. In this case, an argon laser sheet parallel to the pipe axis is used to illuminate the film and the images are recorded by a CCD camera placed perpendicular to the laser sheet. Different zones are analysed from the inlet of the convergent section to the outlet of the diffuser.

The film thickness is determined from a film conductance method described by Hewitt [6]. It consists of measuring the electric impedance between two flush-mounted electrodes.

5.1.2 Results

5.1.2.1 Visualisation of the liquid film behaviour through the Venturi meter

Examples of visualizations of the liquid film through the Venturi meter are shown in Figure 7. The results indicate that the film behaviour depends mainly on the location and on the liquid volume flow rate Q_{v_l} . As a matter of fact, even if an amplification of the disturbance is observed when the gas volume flow rate Q_{v_g} is increased, the influence of the gas velocity does not seem to be the main parameter. On the contrary, the film characteristics change greatly when the liquid flow rate is increased. In the convergent part of the meter, the gas acceleration induces a diminution of the wave amplitude and a thickening of the film. Nevertheless, the movies reveal instantaneous breaking of waves linked to entrainment. For the higher liquid flow rates tested, an intermittent appearance of large waves is observed. At the end of the convergent section, the waves seem to be disorganised. In the throat section, the film becomes thicker and the wavelength greatly diminishes.

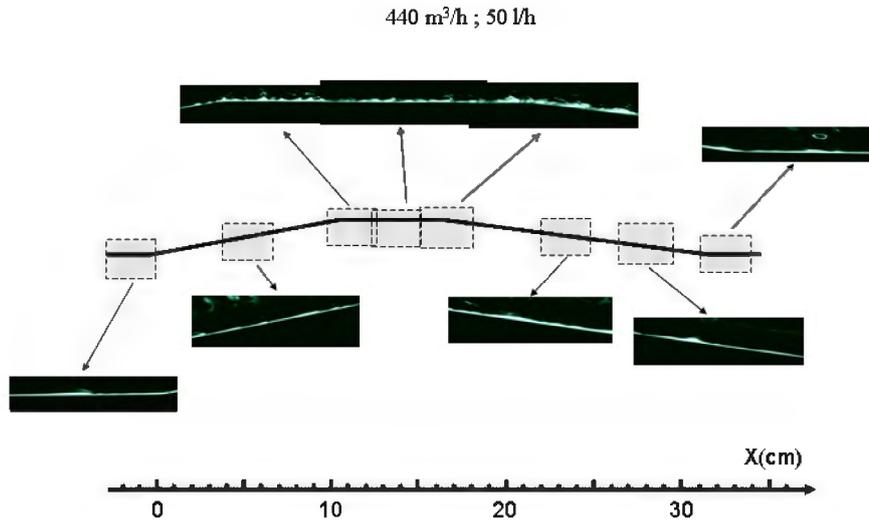


Figure 7 : Visualization of the liquid film behaviour through the Venturi meter ($Q_{v_g} = 440 \text{ m}^3/\text{h}$; $Q_{v_l} = 50 \text{ l/h}$; $Re = 10.7 \cdot 10^4$; $Re_{liquid}=44$)

5.1.2.2 Film behaviour upstream of the convergent section

The analysis of film thickness signals shows that the ONERA's test conditions correspond to 3 flow regimes [7][8]. At low liquid flow rate, the liquid surface is dominated by ripples. For higher liquid flow rate, the disturbance wave regime described by Asali and Hanratty [9] is reached. Among this last regime, two film behaviours are distinguished: the "regular wave" and the "dual wave" regimes. Hanratty [10], observes that when the air velocity is sufficiently high (10 m/s), liquid atomization may occur on the wave crests. Such a result is also observed on visualisations for the highest liquid flow rate.

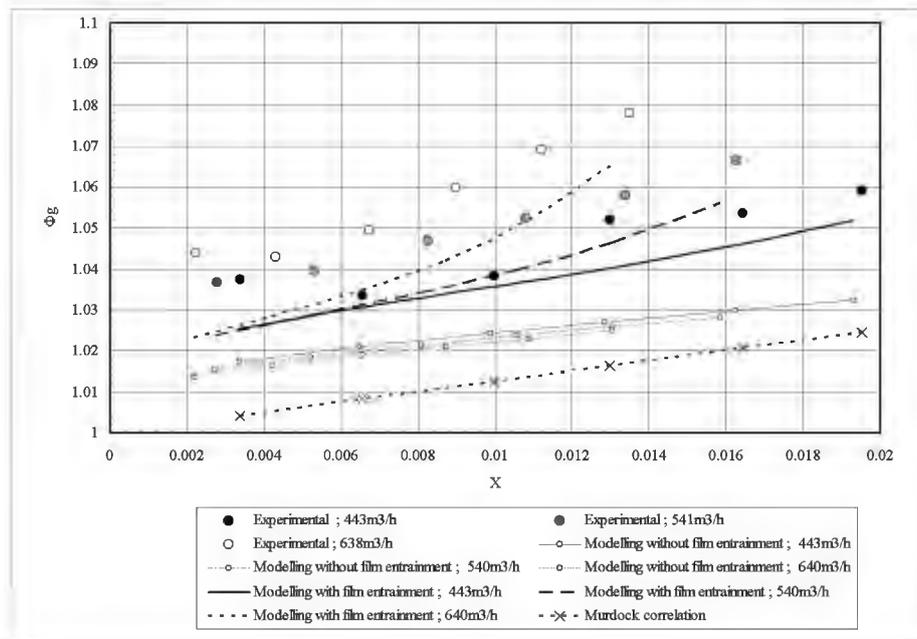


Figure 8 : Correction factor plotted with respect to a Lockhart Martinelli parameter measured in annular flow regime

5.1.2.3 ΔP measurements

The influence of the annular flow regime on the Venturi metering is shown in Figure 8. For low values of the Lockhart Martinelli parameter, the correction factor decreases and then increases. This behaviour may be linked to the film regimes presented previously. The film surface is covered by ripples which do not encourage liquid

atomisation. For sufficiently high liquid flow rates, high amplitude waves appear and liquid atomisation occurs on the wave crests, as observed in the visualisations.

5.2 FLOW MODELLING

The flow modelling method used for this work follows the approach described by van Werven *et al* [11]. Nevertheless some differences appear in particular on the film description. In our model (Lupeau [7], Lupeau *et al* [8]), the flow is divided in two regions: the convergent section and the throat. In each zone, integrated balance equations (mass and momentum conservation) are applied on the gas flow, the liquid film and the dispersed flow. In each pipe section, each flow 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 the gas and droplets and the mass exchange between the film and the droplets due to the entrainment. The model supposes that no mass exchange between the liquid and the gas occurs in the meter (evaporation and condensation). In the convergent section and in the throat, we consider that no mass flux exits between the film and the droplets. We only suppose, as Werven *et al* did, that an atomisation occurs at the inlet of the Venturi throat section. The flow rate and the size of the droplets atomised at this point depends on the film thickness at the convergent section outlet and on the fluid properties. They are deduced from correlations (Lupeau [7], Lupeau *et al* [8]).

Examples of the film thickness and differential pressure distributions calculated by the model are presented in Figure 9 and Figure 10, respectively. The flattening of the film in the convergent observed in the visualisations is reproduced by the model. Furthermore the influence of the liquid entrainment from the film on the pressure is shown in Figure 10. In Figure 5, comparisons with the experimental results indicate that the model is able to predict this parameter within 1.5 %. If we analyse the correction factor calculated with and without taking into account the film atomisation at the throat inlet, we clearly demonstrated the importance of the droplet acceleration on the ΔP measurements. By this way, we observe that it is very important to have a good description of the film behaviour in the convergent because the thickness of this film will have a great influence on the rate of atomisation and at fine on the ΔP increased in the Venturi throat.

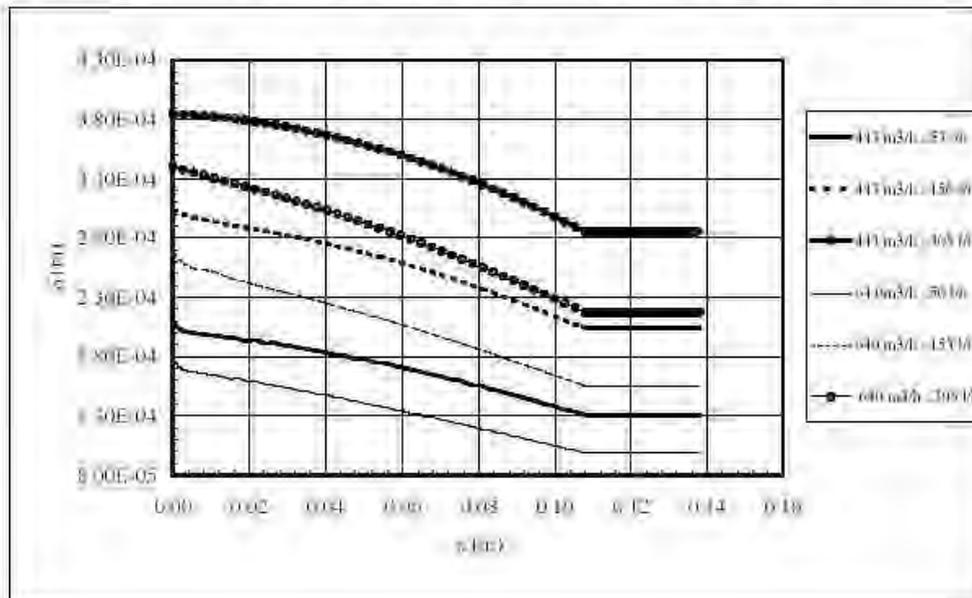


Figure 9 : Film thickness distribution in the Venturi meter calculated by the model

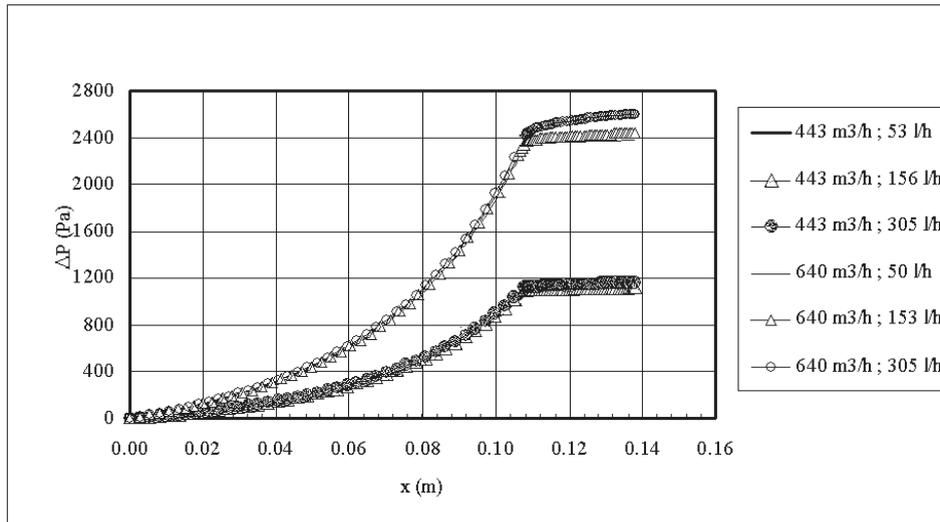


Figure 10 : Differential pressure distribution calculated by the model

5.3 APPLICATION OF MODEL TO HIGH PRESSURE CONDITIONS

The objective of this modelling work is to extrapolate the low pressure results to high pressure configuration. The main difficulty here is to determine the upstream boundary conditions in terms of liquid distribution in the pipe between droplets and liquid film (f factor) and droplet size. One possibility is to determine these quantities from published correlations using the superficial velocities and properties of both fluids. In figure 11, we present an attempt of this approach applied to results obtained on the loop 4. The error bars correspond to 2%. We can observe that, most of the correction factor calculated from the model, reproduced the tests within 2%. Nevertheless, for some points, the deviation is more important. A more precise analysis of the results shows that many factors can explain these results. The first concerns the accuracy of the correlations used to determine the inlet conditions. The second deals with the correlations used in the code. An effort is now needed to improved these correlations.

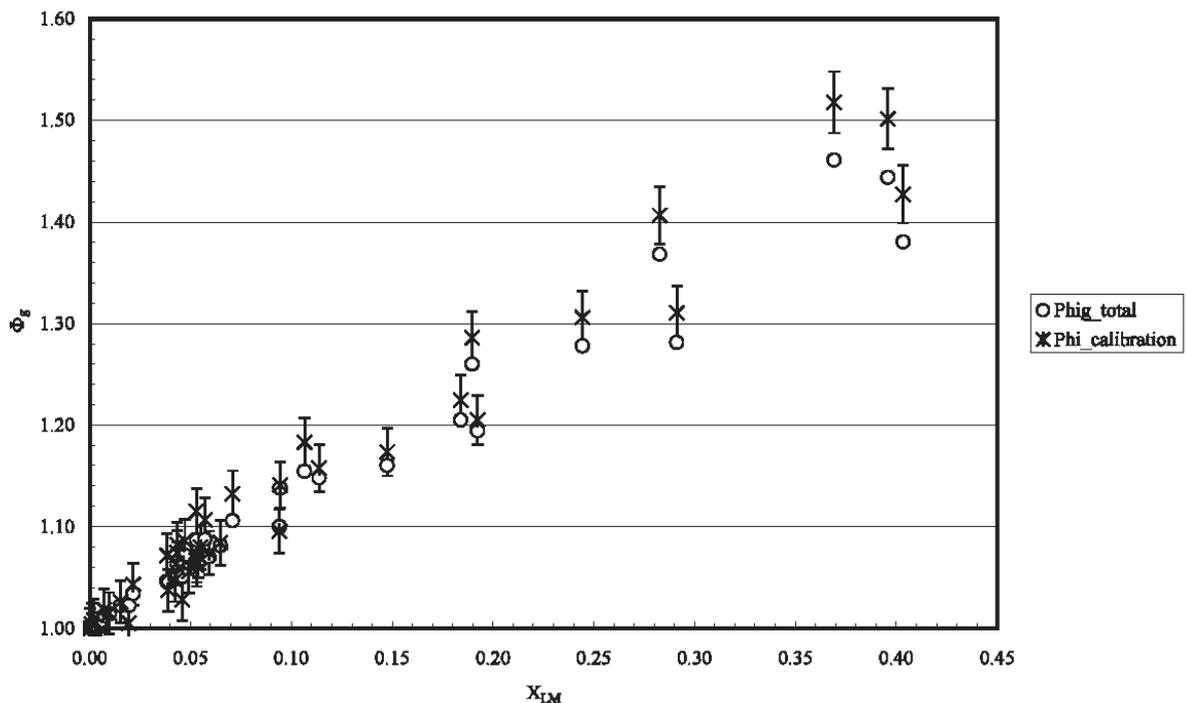


Figure 11 : Validation of the model on high pressure results (Loop 4, 100 bars)

6 CONCLUSIONS

High pressure tests analysis shows that the application of available correlations is not straightforward and published correlations do not necessarily offer the required accuracy when Venturi systems are used in various high pressure conditions. We notice that the accuracy can be improved by selecting Venturi models (mist, film) suited to flow conditions, which indicates that wet gas metering improvement using Venturi meter will require liquid content knowledge but also flow typology information. So the implementation of ΔP based Venturi meter could require more information than expected as such systems will be sensitive to the flow typology upstream the meter and inside the meters also. Information gained so far show also the limitations of ΔP measurements to derive liquid content specifically in 3 phases conditions.

This seems to indicate that wet gas metering will require:

- Three phase meters as the knowledge of the watercut is needed to accurately measure the liquid flows.
- Knowledge of flow morphology upstream meter
- Venturi behaviour information when using Venturi based systems

This is in fact opening a new area for accurate wet gas metering with the following questions:

- Shall we consider wet gas flows as significantly different from multiphase flows ?
- Shall we measure liquid repartition / structure like film thickness ...?
- Shall we still use Venturi meters which are generating flow pattern modification ?

An experimental and modelling work performed on a two phase flow varying from annular to dispersed flow regime, proved that the influence of the flow typology can be taken into account in a one dimensional model to predict accurately the correction factor. This approach verified on low pressure tests, was applied to higher pressure configurations. Even if encouraging results were obtained, it seems now necessary to continue this modelling effort in order to ameliorate the prediction of the flow regime upstream of the Venturi meter.

7 BIBLIOGRAPHICAL REFERENCES

- [1] Steven R., "Wet gas metering", PhD Thesis, University of Strathclyde, Glasgow, (2001)
- [2] DeLeeuw H.: Wet gas flow measurement by means of a venturi and a tracer technique, North sea Flow measurement Workshop, (1994)
- [3] DeLeeuw H.: Venturi meter performances in wet gas flow, *B.H.R. Group 1997 multiphase*, 567-582, (1997)
- [4] Bissières D, Couput J.P , Estivalezes J.L., Gajan P. , Lavergne G. , Strzelecki A., Wet gas flow simulation for venturi meters, 1st North America Conference on Multiphase Technology, Banff, (1998)
- [5] Lupeau A., Escande J., Couput J.P., Gajan P., Strzelecki A., Influence of the characteristics of an annular dispersed flow on the behaviour of a Venturi meter, 4th North America Conference on Multiphase Technology, Banff, (2004)
- [6] Hewitt G.F., Measurement of two phase flow parameters, Academic Press, (1978)
- [7] Lupeau A., Etude de la modélisation du comportement d'un écoulement annulaire dispersé. Application à la mesure de débit de gaz humide à l'aide d'un débitmètre à venturie, PhD Thesis, Supaero, 2005
- [8] Lupeau A., Platet, Gajan P., Strzelecki A., Escande J., Couput J.P., Influence of the presence of an upstream annular liquid film on the wet gas flow measured by a Venturi in a downward vertical configuration, accepted for publication in *Flow Measurement and Instrumentation*, 2005.
- [9] Asali J.C., Hanratty T.J., Ripples generated on a liquid film at high gas velocities, *Int. J. of Multiphase flows*, 19(2), (1993) 229-243
- [10] Hanratty T.J., Interfacial instabilities caused by air flow over a thin liquid layer, In "Waves on fluid interfaces" (edited by Meyer, R.E.), Academic press, New York, (1983) 221-259
- [11] van Werven M., van Maanen H. R. E., Ooms G. and Azzopardi B. J., Modeling wet-gas annular/dispersed flow through a Venturi, *AIChE Journal*, 49(6), (2003), 1383-1391

