Behaviour of Venturi meters in two-phase flows

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ABSTRACT

Needs for accurate and reliable on line metering of two-phase flows (gas and/or liquids) are arising for fiscal and allocation reasons when subsea or topside installations are shared by several partners.

This paper describes the work carried out by ELF EXPLORATION PRODUCTION and GAZ DE FRANCE in collaboration with the ONERA research centre to assess and develop accurate methods applicable for gas metering with condensate ("wet gas").

After a review of allocation metering requirements and available techniques for flow rate measurements in high gas fraction conditions (GVF>95%), this paper deals with the behaviour of Venturi flow meters in similar two-phase flows.

The applied methodology, which combines experimental laboratory testing in ONERA, numerical simulation and field evaluation is described. The preliminary results obtained on the Venturi meter in different two-phase flow configurations (annular, mist) are presented. The influence of some flow parameters (liquid content, flow pattern) on the Venturi behaviour is discussed.

INTRODUCTION

In oil & gas production, there is a need to meter well and field productions for reservoir management but also for allocation or fiscal purposes. This has been classically performed using conventional meters with test or production separators.

For the last few years, operators and manufacturers have started research and development to come up with cost effective metering solutions using multiphase metering. One of the target was, in the early days, to develop multiphase meters to replace test separators in a large range of water cuts and gas volume fractions. Accuracy in the range of +/-10% for each phase (oil, gas and water) has been generally accepted by operators for such a service and there are now several examples of multiphase meters in operation, especially on some ELF developments in the Middle East and West Africa.

Where several owners are involved, multiphase meters with higher accuracy will be required: this will be the case of marginal fields developed through existing installations or in subsea applications where several joint ventures will share common pipelines for CAPEX reduction.

This paper describes some work carried out by ELF EXPLORATION PRODUCTION, GAZ DE FRANCE and ONERA to improve accuracy and reliability of metering systems usable on gas/condensate fields where well effluents are composed of gas mixed with liquid condensate or water.

In this first phase, the work has been focused on the use of Venturi meters in two-phase flows, because they are already used by operators for wet gas metering in third-party allocation and there are several designs already available for topside, subsea, high pressure and high temperature applications.

This paper covers our current field applications, the improvement requirements, the study methodology, the experimental and numerical results obtained so far and the future work.

1 METERING and ALLOCATION

a/Allocation requirements

Due to economic reasons, more and more wells and fields are sharing a common processing platform or common gas transportation system. In that case, allocation metering systems have to be defined and implemented to measure gas and liquid productions with an acceptable accuracy. Based on these figures, allocation calculation will determine final sales products attributed to the different owners.

For allocation purposes, typical accuracy of 1% to 2% on the main stream component (gas or liquid hydrocarbons) quantities will be required. These figures are significantly higher than figures generally accepted for reservoir monitoring purposes which are in the 10% range.

b/Metering schemes for allocation

Due to multiple ownerships, well or field metering can require independent inlet separators just for metering purposes.

Alternative solutions based on two-phase or three-phase flow measurements have already been implemented because the cost reduction is very significant compared to solutions with separation.

In some cases, they allow the platform design to be simplified and can avoid specific well head platforms to be installed.

The figure 1 gives as an example an ELF case in which gas wells connected to a mother platform are metered without separation before being commingled and processed with other streams. In this situation, the owners of these wells and of the other fields are different, thus accurate gas measurements are required for allocation.

Typical figures for such wells are condensate mass fraction of about 5% with a pressure of 60 bar a, and a temperature of 30°C.

c/ Two phase-flow meters for allocation purposes
Standard multiphase meters have been designed to give a medium accuracy in a large range of flow regimes and gas volume fractions, but for the time being, they do not necessarily match our requirements for allocation purposes.

As there is no evidence that accurate multiphase flow meters covering the whole range of flow regimes and fractions can be available before a few years, we are first investigating the possibility of achieving accurate flow measurements in two-phase flows on some specific applications such as gas with low liquid content (wet gas).

As a first step, we have focused on Venturi meters because their performances for gas flow rate measurements are claimed to be in the +/-4% range for gas volume fractions higher than 95%, and also because such meters are already in use on some of ELF operational installations.

2.VENTURI FOR GAS CONDENSATE FLOW MEASUREMENTS

a/ Flow regimes in wet gas applications
Practically, we handle "wet gas" applications in which the effluent is gas with an entrained liquid phase. The gas volume fraction GVF at line conditions is generally higher than 95%.

$$GVF = \frac{Q_{vg}}{Q_{vg} + Q_{vl}} * 100$$

In two-phase flow problems, flow regimes are described by classifying the most obvious types of interfacial distribution. This classification depends on the pipe orientation. As an example, these regimes are represented in figures 2 for horizontal flow.

The flow regime can be predicted in the pipe from flow patterns maps or numerical simulation tools. Liquid volume fraction in some wells does not exceed 1 or 2% and in this case the flow regimes vary from annular flow to dispersed flow.

Two-phase flows[1,2], (figure 3) can be described using the Froude numbers Fr_g and Fr_l, defined below, as

$$Fr_g = \frac{U_g}{\sqrt{gD}}\sqrt{\frac{\rho_g}{\rho_l - \rho_g}} \quad \text{and} \quad Fr_l = \frac{U_l}{\sqrt{gD}}\sqrt{\frac{\rho_l}{\rho_l - \rho_g}}$$

where U_l and U_g are the superficial velocity of the liquid and gas phases.

b/ Two-phase flow metering with differential pressure systems

For the measurement of two-phase flows by means of Venturi systems, the main approach is to define a correction factor depending on the flow characteristics in order to calculate the actual flow rate of gas and liquid in the pipe. These corrections use empirical correlations derived from orifice or Venturi measurements.

The mass flow ratio x is defined by :

$$x = \frac{Q_{mg}}{Q_{mg} + Q_{ml}}$$

where Q_{mg} and Q_{ml} are the mass flow rates of the gas phase and the liquid phase. If we suppose that ΔP_t is the actual differential pressure measured on the flow meter with a two-phase flow, then the total mass flow rate Q_{ml} will be :

$$Q_{mt} = C_D \frac{\pi d^2}{4} \varepsilon \frac{1}{\sqrt{1-\beta^4}} \sqrt{2\rho_t \Delta P_t} = Z\sqrt{2\rho_t \Delta P_t}$$

The apparent mass flow rate of gas and liquid will be :

$$Q_{mgs} = Z\sqrt{2\rho_g \Delta P_t}$$
$$Q_{mls} = Z\sqrt{2\rho_l \Delta P_t}$$

In fact, the actual mass flow rates of gas and liquid are :

$$Q_{mg} = Z\sqrt{2\rho_g \Delta P_g} = x \cdot Q_{mt}$$
$$Q_{ml} = Z\sqrt{2\rho_l \Delta P_l} = (1-x) \cdot Q_{mt}$$

Thus, we can define the multipliers :

$$\Phi_g = \frac{Q_{mgs}}{Q_{mg}} = \sqrt{\frac{\Delta P_t}{\Delta P_g}} \text{ i.e} Q_{mg} = \frac{Q_{mgs}}{\Phi_g}$$
$$\Phi_l = \frac{Q_{mls}}{Q_{ml}} = \sqrt{\frac{\Delta P_t}{\Delta P_l}} \text{ i.e} Q_{ml} = \frac{Q_{mls}}{\Phi_l}$$

For an orifice plate in a horizontal pipe, Murdock obtained the following correlation :

$$\Phi_g = 1.26X + 1$$

where X is the Lockhart-Martinelli parameter defined by :

$$X = \frac{\Phi_g}{\Phi_l} = \frac{1-x}{x}\sqrt{\frac{\rho_g}{\rho_l}}$$

Chisholm[4] gives another expression obtained from wet steam measurements with orifice :

$$\Phi_g^2 = 1 + 2.66X + X^2$$

More recently, De Leeuw[2] has 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, the pressure varied from 15 bar to 90 bar and the GVF from 90% to 100%. In these conditions, the Lockhart-Martinelli parameter varies from 0 to 0.3. He observed that the correlation depends on the Froude number Frg and he proposed the following expression for the multiplier parameter, derived from the Chisholm expression.

$$\Phi_g^{\ 2} = 1 + C \cdot X + X^2$$

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

In this expression :

$n = 0.41$ for Froude number between 0.5 to 1.5

$n = 0.606 \cdot \left(1 - e^{0.746\,Fr_g}\right)$ for Froude number above 1.5

3. STUDY METHODOLOGY

Though the flow regimes encountered in industrial application are well defined, the flow characteristics (liquid phase distribution, droplet size, liquid film thickness) are not easily available and we do not know in detail their influence on the meters (errors) and on the correlations.

An overall approach based on experiments and numerical simulation has been developed using ONERA facilities. This was organised in three steps :

- Low pressure investigations (experiments and simulation)
- Extrapolation to field conditions by numerical simulation
- Validation of simulation results through tests on industrial site or high pressure loops.

The first step is aimed at having a more refined understanding of the physical phenomena which implies a precise measurement of the flow characteristics. In parallel, these experimental results allow validation of the flow simulation approach.

In the second step, the numerical approach allows the prediction of the behaviour of the meter submitted to the actual flow conditions.

In the last step, experiments performed at high pressure conditions will validate the results obtained during the second step.

In the following section we present the experimental and numerical tools used during the study.

a/ Experimental program

ONERA wet gas test facility

The wet gas tests are carried out at low pressure on the ONERA experimental flow loop (figure 4). The gas flow (air) is generated by means of high pressure tanks. The gas flow rate is controlled by a sonic nozzle located upstream the test section in a range of 0 to 650 Sm3/h. The mass flow rate of liquid (water) can be varied from 0 to 250 l/h. This loop can be used from atmospheric pressure to 5 bar.

The flow loop is composed of :

- an horizontal section (25 pipe diameters long (D = 100 mm)),
- a flow conditioner,
- a liquid injector which can produce different types of two-phase flows,
- a test section where the device under test (Venturi meter or other systems) is located
- a separator to recover the liquid.

The test section can be placed following three different pipe work orientations, i.e. horizontal, vertical upwards or vertical downwards.

Tested Venturi under test

A Venturi meter with a beta ratio equal to 0.6 has been tested. The upstream internal diameter is equal to 138 mm and the throat diameter to 101.1 mm. Two models have been designed, one in metal for pressure measurements, and the other in perpex for flow visu alization or optical measurements.

Test conditions

The results presented in this paper are obtained for two pressure values (1 bar and 1.5 bar) and gas flow rates between 350 m^3/h and 630 m^3/h. In these conditions the gas Froude number varies from 0.442 to 0.825. The liquid flow rate ranges from 0. to 250 l/h.

b/ Numerical simulation

Computational code

The calculations are performed with a code developed at ONERA in order to predict flow phenomenon in combustion chambers. It uses an *Eulerian-Lagrangian* approach because this permits an easy introduction of various physical models for the liquid phase behaviour. The method refers to Eulerian gas phase modelling, and *Lagrangian* liquid phase modelling. Details of the numerical technics can be found in Bissières et al[5].

Computational grid and flow conditions

These flow calculations are performed on a Venturi flow meter with a 2D body-fitted grid. The grid contains 153 meshes in the longitudinal direction and 31 in the transverse one (figure 5).

At the inlet of this domain, we consider that the gas phase is composed with air at ambient pressure and temperature. The inlet velocity profile is uniform with a bulk velocity equal to 25 m/s. The turbulence level is set to 5% and the length scale l to 3 mm. The liquid phase is simulated by water. Two values of the mass flow ratio of gas are considered (91% and 66%). The distribution of the liquid flow rate along the inlet pipe radius is set constant.

Three droplet sizes are considered successively (10 mm, 20 mm, 100 mm).

4. SUMMARY OF RESULTS

All the results obtained during this study are plotted in figure 6 in the form of Φg distribution versus the Lockhart Martinelli parameter. They are compared to the Murdock and De Leeuw correlation. In the latter, the variation of the Froude number taken into account in the experiments implies a unique curve correlation ($0.5<Fr_g<1.5$ which imposes a constant value of n in the De Leeuw correlation). Note that the Chisholm and Murdock correlations are equivalent.

a/ Experimental results

Globally we can note that all the experimental results are located between the Murdock and De Leeuw correlations. We also observe that when the air flow rate increases, the result tends to the De Leeuw prediction.

When we look at the results obtained at atmospheric pressure for which the Froude number varies from 0.442 to 0.825, we observe that the slope of the correction curve increases with the gas Froude number. This tendency has been already noticed by De Leeuw[2].

Nevertheless, if we compare results obtained at two different pressures, this tendency is not verified. This discrepancy can be explained by a flow regime modification obtained during the tests. As a matter of fact, the first flow visualizations show that when the air flow rate increases, the number of droplets increases what means that the flow tends to a dispersed flow regime.

This influence of the flow regime can also be deduced from the De Leeuw results from which we can note that the correction diminishes with the Froude number and that, in parallel, the flow changes from annular dispersed regime to stratified regime.

This explanation will be verified by a characterization of the two-phase flow.

b/ Simulation results
In figure 7, the droplets pathes are plotted for the three droplet sizes and for a x value equal to 91%.

We observe that, the larger their diameter is, the less they follow the gas flow. This phenomenon is due to the variation of the relaxation time of the droplets with respect to their diameters. In particular we note an increase of the number of wall impacts. Nevertheless, the results obtained with the 100 μm droplets must be analysed carefully. As a matter of fact, the interaction taken into account between the wall and the droplets is, for this work, simplified.

Though, in this simulation, the larger droplets, which do not follow the gas flow, impact the wall on the converging parts of the Venturi and rebound against it like a ball. This explains why, in figure 7, all the particules are located in the centre of the pipe downstream the flow meter. In the real world, these droplets would form a liquid film, which would be transported downstream and, certainly, would be disintegrated downstream the throat. These phenomena must be studied in more details in the future.

The pressure distribution on the wall is plotted in figure 8. The influence of the mass flow rate ratio and of the droplet size is enhanced on this figure. For the smaller droplet sizes with a mass flow ratio of gas x equal to 66%, a large effect is obtained. In this case, the droplets, which are small enough to follow the gas flow particules fall in a separate zone that appears in this flow configuration downstream the Venturi.

Based on the pressure fields, it is possible to calculate the factor of correction used to take into account the influence of the liquid phase on the measured differential pressure. These results can be compared with experimental correlation obtained in the present study or published in the literature (figure 6).

We can note that, for the smallest droplets, the corrections obtained are well above the De Leeuw correlation and that for the highest ones, the correction is close to those measured in our experiment.

In order to explain this tendency, we have plotted, in figure 6, a new correlation that only takes into account the variation of density of the fluid due to the presence of liquid. As a matter of fact, if we consider that the droplets follow the air flow with no slip, we can calculate an equivalent density ρ_t from a momentum conservation point of view . If we consider that the slip velocity ratio between the two phases is equal to 1, the equivalent density can be calculated from the following expression :

$$\rho_t = \frac{\rho_g}{x + (1 - x)\frac{\rho_g}{\rho_l}}$$

In the case of water droplets in air flow at atmospheric pressure this expression can be reduced to :

$$\rho_t = \frac{\rho_g}{x}$$

From the general formulation given in section 2b), we obtain the following equation for the correlation parameter plotted in figure 6 (Equivalent density correction):
For the smaller droplets which verified this hypothesis, the flow calculations are in a good agreement to this law. For bigger droplets, slip and wall interaction phenomena appear and this correction is no longer verified and numerical results tend to the classical laws. It is interesting to note that two-phase flow characterizations performed with the same type of injector than those used in our experiments give a mean droplet size around 100 µm.

$$\Phi_g = \sqrt{1 + X\sqrt{\frac{\rho_l}{\rho_g}}}$$

5. CONCLUSIONS AND FUTURE WORK

The first results we have obtained are in some cases in accordance with published results. Experimental results and numerical simulation demonstrate that correlation are to some extent sensitive to Froude numbers, to changes in flow regimes (from dispersed to annular dispersed) and to droplet size effects. They indicate that there is no reliable correlation to correct Venturi measurements in wet gas flows with a good accuracy.

For the time being Venturi meters can obviously be used for allocation purposes, but they will still require frequent calibration using test separator until a robust correlation is proposed and accepted.

The work in progress and the methodology in use (experiments and simulation) will allow to quantify effects of fluid composition and flow morphology on wet gas measurements using Venturi.

We expect to come up in the next future with additional information on magnitude of errors due to different parameters and with improved correlation or guidelines for choosing the best correlation to match the allocation requirements.

Wet gas measurements for allocation purposes really corresponds to a common need from different users and manufacturers. This has been clearly understood by International Standardisation Organisation and a specific Sub-Committee SC3 - Upstream Area has recently be created in ISO TC 193 - Natural gas to address questions like upstream measurements (wet gas or raw gas for instance) and allocation procedures.

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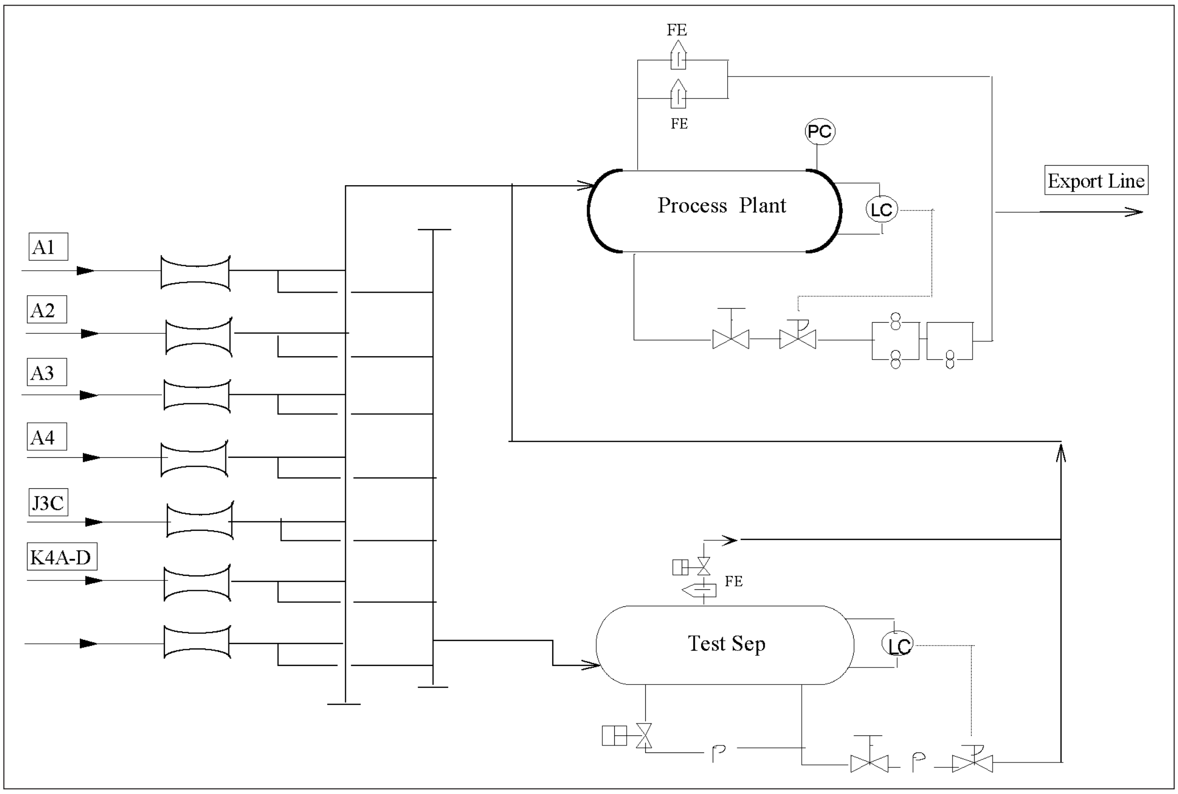

Figure 1 : Metering sheme

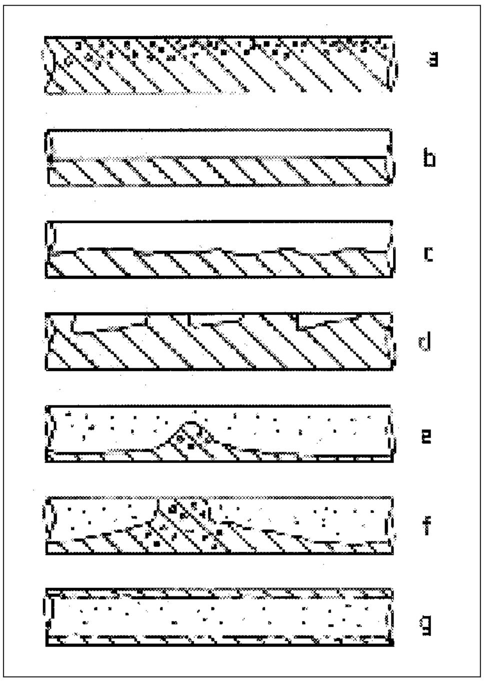

Figure 2 : Gas-liquid flow regimes in horizontal (a : bubbly, b : stratified, c : wavy, d : plug, e : semi-plug, f : slug, g : annular)

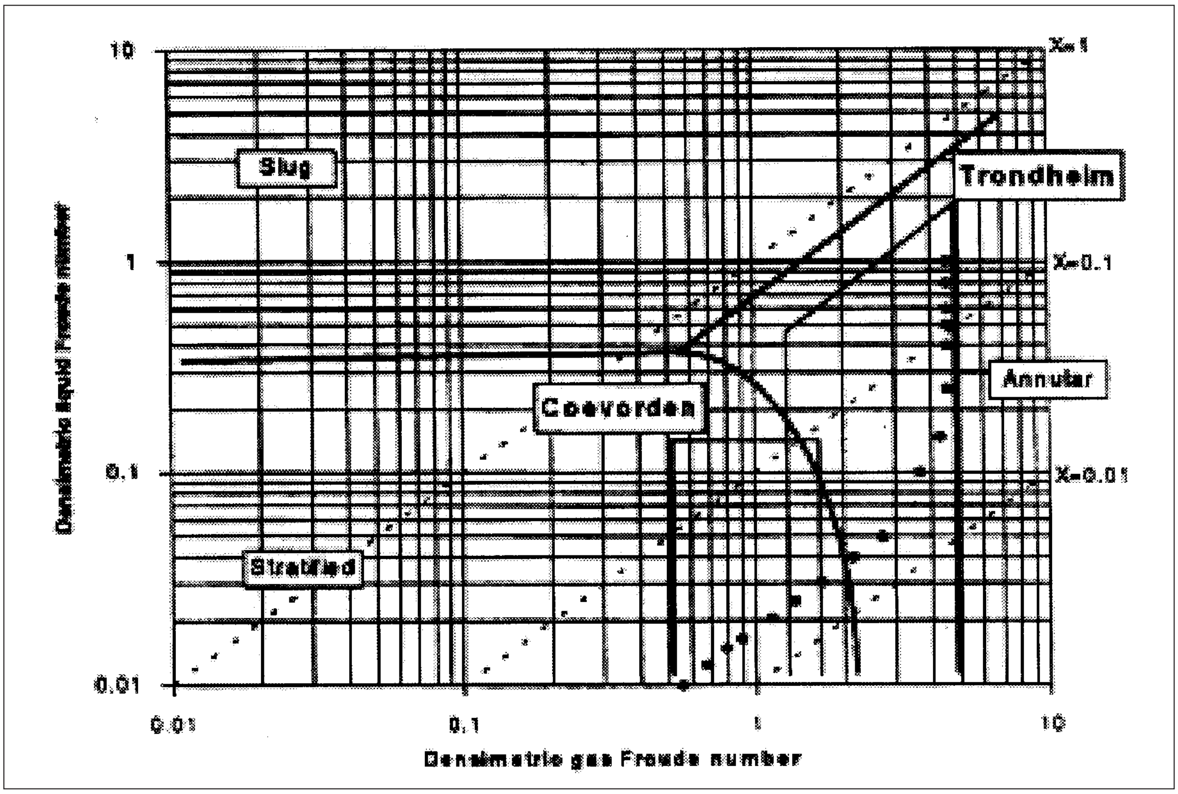

Figure 3 : Flow map obtained by De Leeuw_

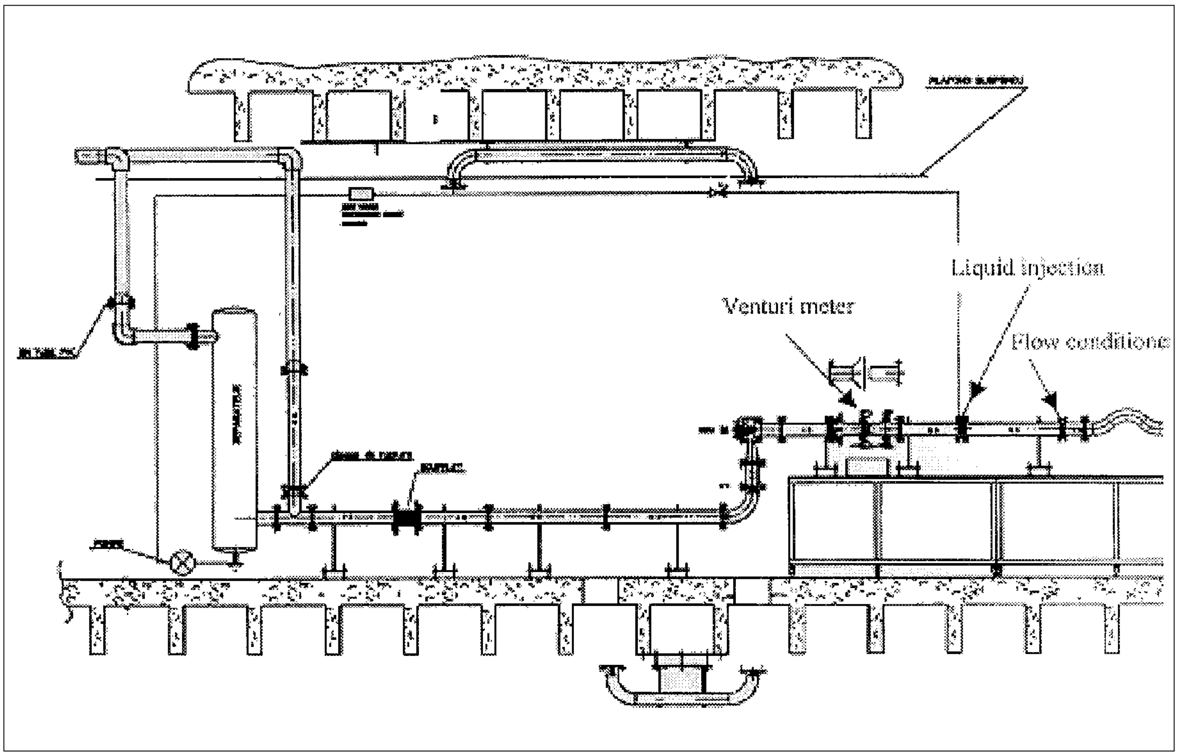

Figure 4 : Experimental test set-up

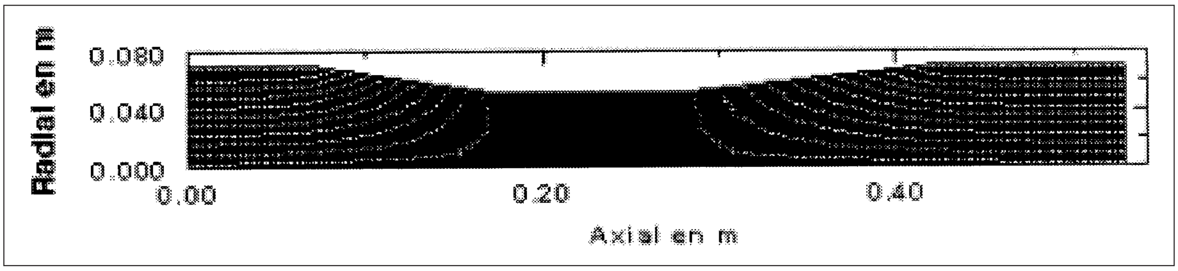

Figure 5 : Venturi mesh

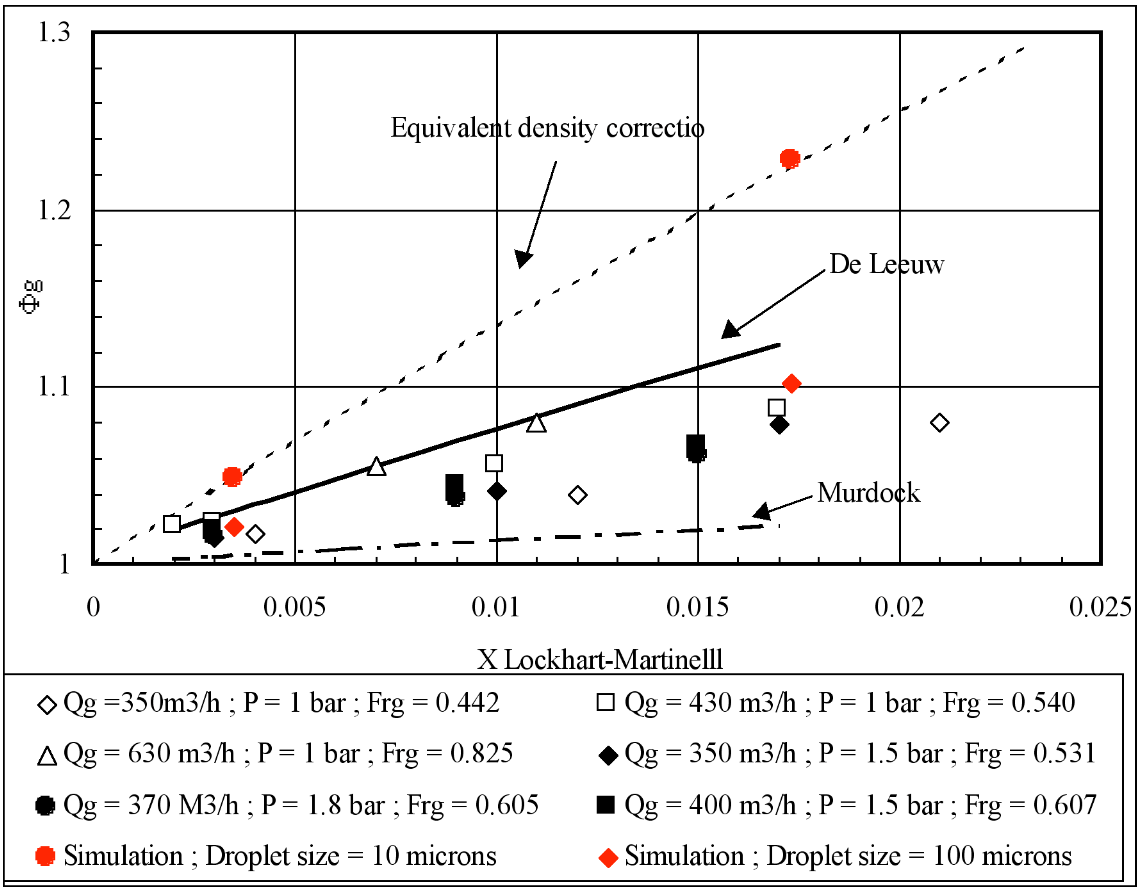

Figure 6 : Correlation parameter versus Lockhart Martinelli coeffient

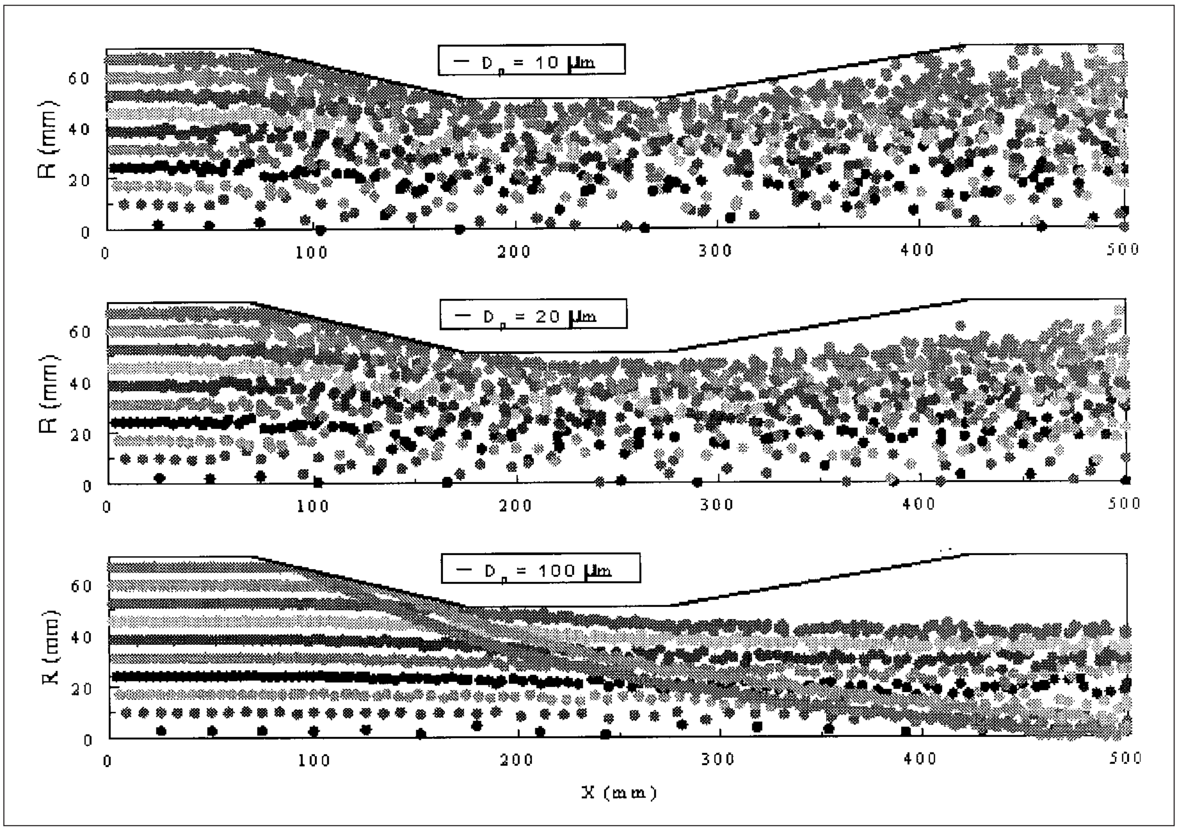

Figure 7 : Droplet pathes for x = 91 %

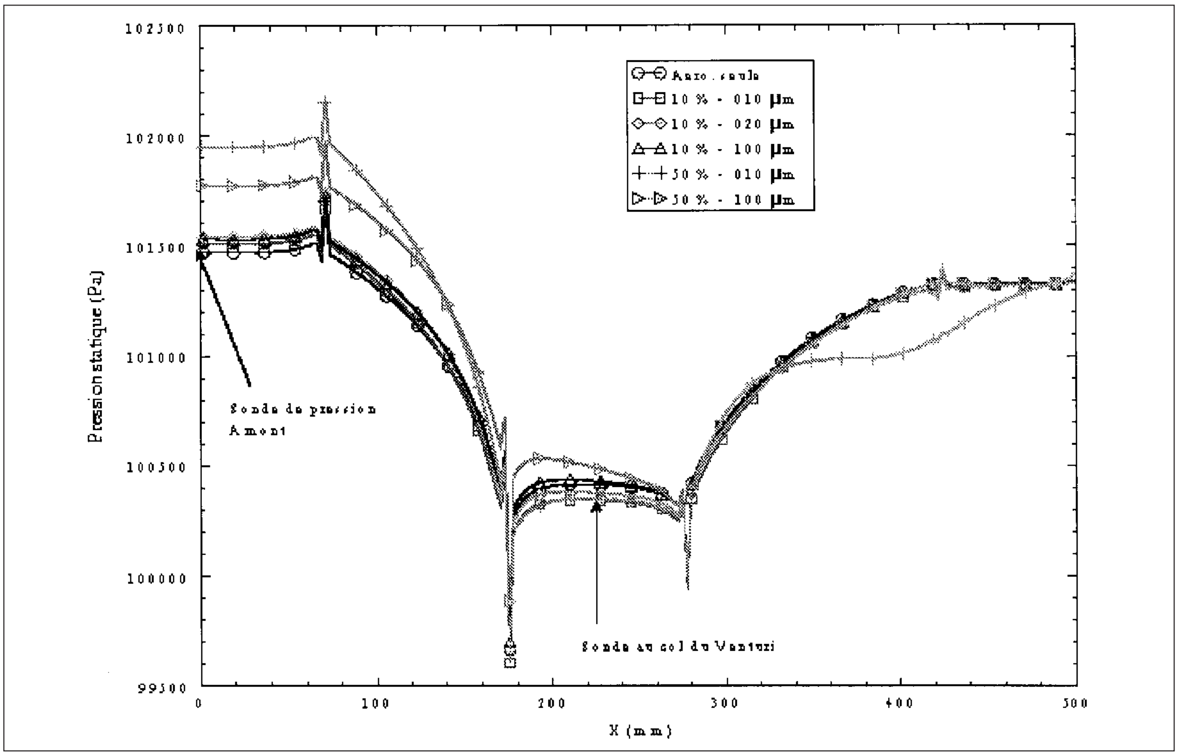

Figure 8 : Wall pressure distribution . The different liquid rates are represented with the ratio

$$\frac{Qm - liquide}{Qm - gas}$$