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VENTURI FLOW METERS BEHAVIOUR IN HIGH PRESSURE 3 PHASES WET GAS CONDITIONS

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1 INTRODUCTION

Subsea or topside developments of gas & gas condensate fields are more and more demanding regarding wet gas metering solutions for reservoir monitoring, production optimisation, internal or contractual / fiscal allocation.
Such increasing number of applications has generated both the marketing of a variety of wet gas flow meters solutions and also a significant number of international ISO documents (ISO /TR 11583:2012 - Measurement of wet gas flow by means of pressure differential devices inserted in circular cross-section conduits and ISO/DTR 12748:2014 Wet gas flow measurement in natural gas operations) to share and start to standardise practices.
In addition to that, accuracy improvement of wet gas meters has also been an ongoing issue for operators and regulatory body.
TOTAL as a recognized user of multiphase metering solutions (conventional & wet gas) has launched with ONERA Research Institute in France programs to model Venturi flow meter behaviour in high pressure wet gas flows in order to improve both gas measurement accuracy as well as liquid accuracy.

2 WET GAS FLOW METERING CHALLENGES

In upstream field applications, so called wet gas is generally a 3 phase flow i.e. a gas predominant flow with both water and condensate liquids. Most of wet gas flow metering solutions developed, marketed and used so far is using differential pressure measurements across Venturi combined with additional fractions measurements to derive gas, condensate and water rates with the required accuracy.

The current trends in the development of this Wet Gas Flow Meters (WGFM) are to develop stand-alone systems permitting to measure the mass and volumetric flow rates of the different fluids without external information from costly separation procedures.

Technology should allow to determine some liquid hold ups, the water to liquid ratio, and the water salinity or, in some extend the flow regime inside of the meter.

In most cases, the calculation of the different flow rates from the differential pressure measured on the Venturi meter requires to determine the over reading coefficient induced by the liquid (water & condensate) presence in the pipe i.e. to interpreted differential pressure measurements.

3 3 PHASES VENTURI METER MODELLING APPROACH

A significant amount of work was done to estimate these over readings due to and different empirical or semi empirical correlations were proposed to deduce the gas flow rate from the pressure measurements performed across the meter (Murdock, Chisholm, de Leeuw, Reader-Harris, Steven...)

Such work is generally based on two phase experiments (gas + single liquid) and does not necessary consider the corresponding wet gas flow regimes which can vary from annular flows to dispersed flows following the liquid content and properties, the pressure or the flow meter installation condition (pipe orientation, upstream piping).

It is known that the simultaneous presence of hydrocarbon liquid and water in the pipe induced particular flow behaviour called "inversion phenomena". Recent works shown that this phenomena induced modifications on the flow inside of the the flow meter and consequently, on the over reading coefficient (Gajan et al [1]).

In order to take into account the flow regime and the fluid properties influences, a new approach based on a flow modelling of the two phase flow behaviour inside of the meter was proposed by Van Werven et al [2], Lupeau et al [3],Salque et al [4]. Such approach uses semi-empirical correlations which were mainly obtained for low pressure conditions in laboratories.

In principle, the advantage of a modelling approach is that it can be incorporated in a calculation code and then implemented in the software of the WGFM.

This approach can be very useful during the life of the shell where the flow condition may change from the beginning of the production to the end and the over reading determination can be adapted to the real situation encountered in the pipelines.

Nevertheless, required steps to use this modelling approach in industrial application are

- first to validate the models on well documented flow conditions
- And second to compare the over reading predicted to data base obtained with realistic flow condition and in particular at high pressure.

This is what will be discussed in the following chapters which are focusing on the model validation with well characterised flows and on the confrontation of the flow modelling results with high pressure tests.

4 3 PHASES TEST CONFIGURATIONS

The results presented in this paper were obtained on three test trials performed in laboratory at atmospheric condition at ONERA facilities and on two high pressure facilities with two different Venturi meters geometries and two pipe configurations. The high pressure data sets were obtained from tests performed at CEESI and DNV Kama facilities.

4.1 ONERA test configuration

The objective of these tests was to validate the different semi empirical flow models used in the WEGMOVE code on a flow pipe configuration representative to the actual arrangement used in industry. The flow consists in air mixed with water and Finavestan oil. The pipe diameter was equal to 50 mm. A 0.6 β ratio Venturi meter designed from the ISO recommendations was placed 35 D downstream of a blind Tee in a downward vertical flow direction. This flow direction was chosen in order to eliminate counter liquid flow linked to gravity which can occur at low pressure. Oil and water were injected upstream of the blind tee through spray atomizers. The Test bench permit to measure the liquid distribution between the spray in the pipe core and the wall filming, the liquid film thickness and the droplet size. The two last parameters are only accessible in air/water condition.

Two air flow rates were used (180 and 250 m3/h). The total liquid flow rate was fixed to 180 l/h and the Water Liquid Ratio (WLR) was varied from 0 to 100 %.

4.2 CEESI test configuration

The aim of these tests was to analyse the Venturi behaviour in controlled flow configuration. In particular, it was important to place the meter in a reference flow condition obtained with a sufficient upstream straight pipe length. For a two phase flow, Kataoka and Ishii [5] defined the distance needs to obtain an equilibrium condition.

In order to obtain the desired flow conditions the Venturi meter was placed horizontally 144 D downstream of a 90° bend. The venturi was designed according to the ISO recommendations. The pipe diameter is equal to 0.194 m and the β ratio to 0.6.

The test chart contains 65 points for which the Gas Volume Fraction (GVF) varied from 95% to 100% and the Water Liquid Ratio (WLR) or the Water Cut from 0 to 100%. The range of the different parameters is indicated in table 1.

4.3 DNV KEMA test configuration

For this test, the Venturi meter was place vertically upward with a blind Tee placed upstream. This configuration is representative to many set up used in real flow metering condition. The β ratio is equal to 0.7. The wet gas is formed with natural gas mixed with EXXOL D120 as hydrocarbon liquid and water with different salinities.

Table 1 – Test conditions

Parameter	CEESI test range	DNV KEMA test range
j_g (m.s^{-1})	6 – 16	6 – 26
j_w (m.s^{-1})	0.25 – 0.75	0 – 0.61
j_o (m.s^{-1})	0.25 – 0.75	0 – 0.65
P (bar)	73 – 76	10 – 25
ρ_g (kg.m^{-3})	58 – 61	9 – 23
ρ_w (kg.m^{-3})	998	1000
ρ_o (kg.m^{-3})	737	711 – 820
μ_g (kg.m^{-1}.s^{-1})	1.36 10^{-6}	1.25 10^{-5}
μ_w (kg.m^{-1}.s^{-1})	0.78 10^{-4}	1.1 10^{-3}
μ_o (kg.m^{-1}.s^{-1})	1.61 10^{-3}	3.3 10^{-3} – 47 10^{-3}
σ_w (N.m^{-1})	0.073	0.073
σ_o (N.m^{-1})	0.0105	0.025

5 FLOW MODELLING

In order to predict the correction factor, a flow modelling method described in Lupeau et al [3] and Gajan et al [5] is used. The balance equations are solved in a numerical code.

The flow is divided in two regions: the convergent and the throat. In each zone, integrated balance equations (mass and momentum conservation) are applied on three flow entities; the gas flow, the liquid film and the dispersed flow. In each pipe section, 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 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).

Furthermore, in the convergent zone, no mass transfer between the film and the droplets is considered. On the contrary, an atomization of the liquid film is taken into account at the convergent/throat junction.

The volume flow rate of liquid atomized is deduced from a correlation obtained by Salque et al [6]. This correlation is based on a Weber number computed from the local interfacial shear stress τ_i exerted by the gas on the liquid film and the wave amplitude as length variable. The interfacial shear stress is computed from the Wallis correlation.

To define the size of the droplet atomized, an empirical correlation proposed by Azzopardi and Govan [7] is used.

The boundary conditions at the inlet of the convergent section concern the gas and droplet velocity, the liquid distribution between the droplets flow and the wall liquid film and the droplet size. 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 liquid distribution *f* corresponds to the ratio between the droplet flow rate and the total liquid flow rate. Two correlations can be used; the first is the well-known Ishii correlation [8] developed from low pressure experiments with water and the second was developed from tests performed in the 30 – 90 bar pressure range with steam water. The droplet size is deduced from the Azzopardi and Govan correlation. 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 water/hydrocarbon mixture is considered as a unique equivalent fluid with physical properties computed using the water cut value [5].

The overreading coefficients measured or determined from the code are compared to the correlation proposed in ISO/TR 11583 report through tests performed in high pressure conditions on third party flow loops. It was proposed by Reader Harris and Graham [9]. The gas mass flow rate measurement with a Venturi meter depends on two parameters, the discharge coefficient C_D and the over-reading correction factor Φ_g.

The discharge coefficient is no longer deduced from dry gas tests but from the following expression:

$$C_D = 1 - 0.0463 \cdot \exp\left(-0.05 Fr_{g,th}\right) \min\left\{1, \sqrt{\frac{X}{0.016}}\right\}$$

where

$$Fr_{g,th} = \frac{Fr_g}{\beta^{2.5}}$$

The over-reading correction factor Φ_g is calculated with the same expression as proposed by de Leeuw [10]:

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

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

The n exponent is computed by the following expression:

$$n = \max\left\{\begin{matrix} 0.583 - 0.18\beta^2 - 0.578\exp\left(\dfrac{-0.8 Fr_g}{H}\right) \\ \\ 0.392 - 0.18\beta^2 \end{matrix}\right\}$$

where H depends on the liquid. It is equal to 1 for hydrocarbon liquid, 1.35 for water at ambient temperature and 0.79 for liquid water in a wet steam. It is a function of the surface tension of the liquid.

6 RESULTS OBTAINED

6.1 Validation of the semi empirical correlation at low pressure

In figure 1, the liquid distribution, the film thickness the droplet size and the correction factor measured on the ONERA flow loop is compared to the semi empirical or modelling results. Good results are obtained on the upstream liquid distribution and film thicknesses for pure liquids. For oil/water mixture the comparison can be only done on the liquid distribution. It is obvious the use of the equivalent liquid approach with the Ishii correlation induces large over estimation of the spray flow rate (f tends to 0). Furthermore, the experimental results show an increase of oil content induces first, an augmentation of the droplet flow rate (WLR < 0.6) then a rapid diminution for 0.6 < WLR < 0.8. This behaviour can be linked to inversion phenomena already observed in the literature by Pan [11], Wood et al [12], Açikgoz et al [13]. Concerning the droplet size, a quite good agreement is obtained. Finally, the over reading factor computed by the flow modelling used in the code is satisfactory for pure liquid with a deviation less than 3%. For WLR between 0 and 1 larger deviations are obtained. This is due to the wrong estimation of the liquid distribution observed above.

6.2 High pressure experimental data analysis

The correction factors obtained during the CEESI and DNV KEMA tests are plotted in figure 2. It is observed that the correction factor augments with liquid contents in the flow. Furthermore an influence of the Water Liquid Ratio is clearly obtained. In particular, it is seen that, when the water content augments in the liquid, the correction factor augments first, reach a maximum and then decrease. As indicated before, such behaviour is due to an inversion phenomena observed previously by Cazin et al [14] and Gajan et al [1] for Venturi flow meters. This behaviour is observed on the two data sets, but the WLR corresponding to the inversion phenomena is not the same.

Deviations between measured and predicted over reading coefficient factors are plotted in figure 3. In both cases, the semi empirical correlation deduced from high pressure tests is used to determine to define the upstream liquid distribution.

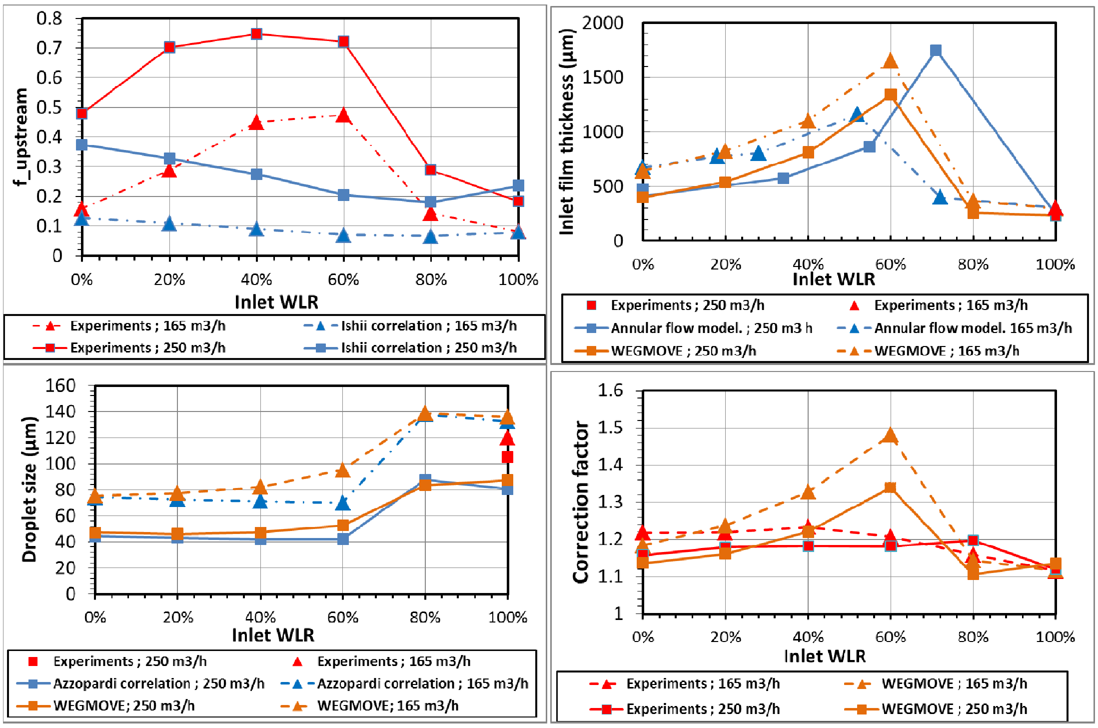

Fig. 1: Validation of the flow modelling at low pressure

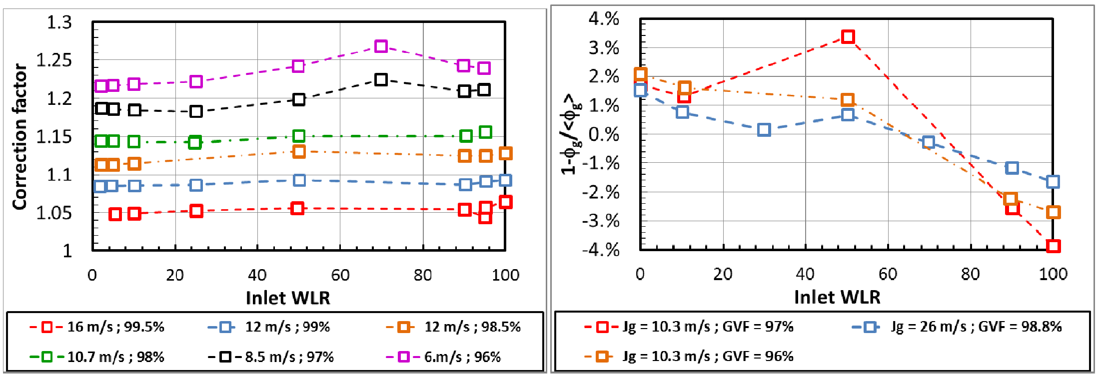

Fig. 2: Influence of the WLR and the GVF on the over-reading correction factors (Left : CEESI; Right : DNV KEMA)

It can be seen that better results are obtained for the two approaches at higher pressure (CEESI). Furthermore the conclusion concerning the more appropriate approach is not evident. For the CEESI tests, the ISO correlation gives better results than the flow modelling predictions in particular for higher Lockhart Martinelli parameters. This is not the case for the DNV KEMA tests. The origin of this different behaviour is not obvious at the moment. Nevertheless, comparison between different semi-empirical correlations shows that the liquid distribution upstream of the meter is a key point of the accuracy of the flow modelling.

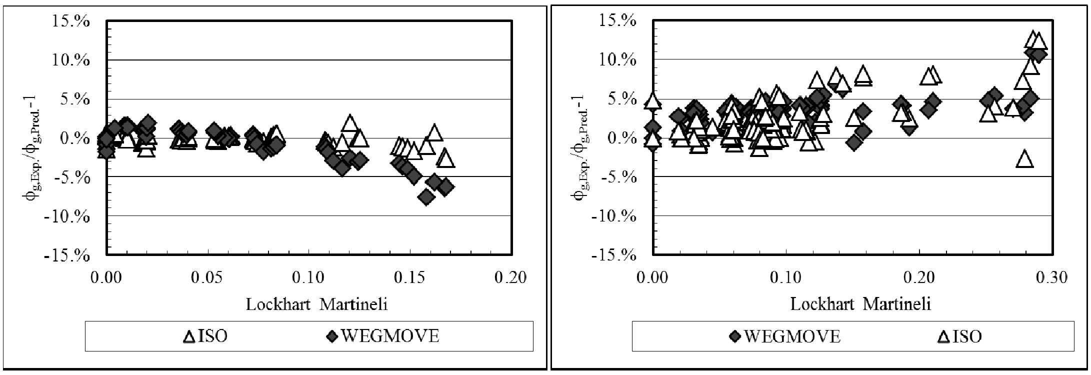

Fig. 3: Deviation between predicted and experimental over-reading correction factors(Left : CEESI; Right : DNV KEMA)

7 CONCLUSIONS

This paper has presented tests of a model based Venturi correction method which is an alternative to published method based on empirical correlation to determine the actual gas flow rate in pipes with a Venturi meter used in wet gas conditions.

The validation of the model performed at low pressure with well-defined flow conditions with a pipe arrangement representative of the WGFMs installation in industry shows that the liquid distribution is well predicted by the Ishii correlation for pure liquids. Nevertheless, the use of a mixture between oil and water give great difference between the prediction and the experiments. The method used to determine the film thickness was validated for pure water flow, and finally the over reading factor prediction is quite satisfactory for pure liquid but not for oil/water mixtures. The differences observed are link to the liquid film distribution upstream of the meter. It is necessary to improve the modelling of this mixture in term of physical properties.

The comparison of the flow modelling prediction with high pressure data bases and prediction from correlations shows a great influence of the pipe arrangement and the flow condition. It seems that the main difficulties come from the determination of the liquid distribution upstream of the meter. This point may be regarded in detail in the future.

Even if difficulties still exist, the development effort need to be continued in the future to define a new generation of smart WGFM which will adapt their measurements to the actual flow configuration.

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