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TWO-PHASE ANNULAR FLOW IN A VERTICALLY MOUNTED VENTURI FLOW METER

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ABSTRACT

In the present research work, the experimental investigation of a vertical upward annular two-phase flow in a Venturi Flow Meter (VFM) is performed. The pressure drops between the inlet and throat section and between inlet and outlet (irreversible pressure drops) are measured and analyzed.

The flow meter is characterized by an inlet diameter of 80 mm and a throat diameter of 40 mm (β=0.5), with equal convergent and divergent angles (θ=21°). The instrument has been tested in a test section, having an internal diameter (D_i) of 80 mm and a total length (L) of about 4 m, with air-water two-phase flow at ambient pressure. The air superficial velocity ranged between 14 and 18 m/s while the water superficial velocity ranged between 0.0008 and 0.005 m/s, so that the flow pattern was annular and the corresponding void fraction was higher than 0.97, while the flow quality ranged between 0.78 and 0.96.

The dependency of the pressure drops on the phases velocities has been analyzed and modeled as a function of the superficial velocities of the phases.

In addition the possibility to derive the mass flow rate of the two-phases from the sensor signals, when the flow pattern does not change, has been analyzed. The developed model allows the evaluation of the flow quality of the mixture with an accuracy of 5% and the estimation of the mass flow rate of air and water with an accuracy of 2% and 30% respectively.

INTRODUCTION

The measurement of two-phase flow parameters is essential for the understanding and for the control of many industrial processes, particularly in the oil and gas, nuclear energy and chemical processing industries. In several applications the flow is characterized by very high or by very low quality values. In the case of high flow qualities the flow is characterized by very high void fraction values, and the flow pattern is usually annular or dispersed (wet-gas). Due to the simple design, the low costs, and the limited maintenance required, the Venturi Flow Meter (VFM) is one of the most used instruments for single-phase mass flow rate measurement, and it is one of the best candidate for two-phase mass flow rate measurement. In two-phase flow, the pressure drops are higher compared to single-phase flow, due to the strong interaction between the phases, that are strictly related with the phases distribution or flow pattern. Considering its technical importance the response of the VFM in two-phase flow has been extensively studied by several authors [1]-[12], and a number of correlations and models have been developed. The well known works of Chisholm [8] and Murdock [9] have been used as guidelines for a new correlation developed by Bizon and Lin [13] and more recently by Moura and Marvillet [14], de Leeuw [15], Steven [16] and Xu [17].

All the correlations have been developed for very high or very low quality flows, and are focused on the correct measurement of the continuous phase, while the mass flow rate of the dispersed phase is usually neglected. In some situations, as for example in nuclear safety simulation facilities, the measurement of the mass flow rate of the two phases is fundamental for a proper analysis of the accident evolution. So that the pressure drops in the VFM have to be modeled as a function of the two phases superficial velocities in order to evaluate the effect of each phase on the total flow meter pressure drops. In this context important information can be extracted from the analysis of the irreversible pressure drops. Compared with the extensive works conducted on the analysis of the pressure drops between inlet and throat section, very few works have been performed on the modeling of the irreversible component. Only recently new phenomenological model have been applied to analyze the pressure drops in those devices [18].

In the present research work, the experimental investigation of a vertical upward annular two-phase flow in a VFM has been performed. The dependency of the pressure drops on the phases velocities has been analyzed and modeled, and the differences with respect to the air single-phase flow have been evaluated.

The predictions of the existing correlations are compared with the experimental pressure drops, and a formulation that predicts the experimental data is presented. Moreover the irreversible VFM pressure drops have been measured and analyzed. The experimental results have been modeled as a function of the flow quality and of the superficial velocities of the phases, showing that additional relevant information on the two-phase flow can be extracted from the test data. In the last part of the work the characterization of the two-phase Venturi pressure drops is used to evaluate the mass flow rate of the two-phases showing that further information can be derived from the measurement of the irreversible pressure drops.

NOMENCLATURE

A_2	[m^2]	throat cross section
C_d	[-]	venturi discharge coefficient
D_1	[m]	inlet section diameter
D_2	[m]	throat section diameter
f	[-]	friction factor
F_a	[m/s]	correction factor for thermal expansion
J	[m/s]	superficial velocity
L	[m]	geometrical length
p_1 - p_2	[Pa]	inlet (1) - throat (2) section pressure drops
Q	[m^3/s]	volumetric flow rate
Re	[-]	Reynolds number
S	[-]	slip ratio
v_1	[m/s]	VFM inlet section velocity
v_2	[m/s]	VFM throat section velocity
W	[kg/s]	mass flow rate
x	[-]	flow quality
Y	[-]	compressibility factor
Special characters		
α	[-]	void fraction
β	[-]	diameter ratio D_2/D_1
ρ	[kg/m^3]	fluid density
θ	[°]	VFM divergent / convergent angle
μ	[Pa·s]	dynamic viscosity
Φ	[-]	two-phase flow multiplier
χ	[-]	Martinelli parameter
Δp	[Pa]	pressure drop
Subscripts		
d		discharge
exp		experimental
est		estimated
g		gas
int		internal
irr		irreversible
l		liquid
tot		total (liquid + gas)
TP		two-phase
V		Venturi

VENTURI FLOW METER CHARACTERISTICS

The derivation of the mass flow rate from the measurement of the differential pressure in a VFM is commonly used for single-phase flow in a wide range of industrial application. The technical standards [19] are, in this case, well defined and verified by several experimental and theoretical models.

The reference equation of the VFM in single-phase flow can be obtained applying the Bernoulli equation (balance between kinetic energy and static energy of a vena fluida) at the inlet and at the throat section:

$$\Delta p = p_1 - p_2 = \frac{\rho}{2} \cdot \left(v_2^2 - v_1^2 \right) \tag{1}$$

so that the volumetric flow rate is given by:

$$Q = \left[C_d A_2 \left(\frac{2\Delta p}{\rho \left(1 - \beta^4 \right)} \right)^{0.5} \right] \cdot F_a \cdot Y \tag{2}$$

The correction factor C_d is introduced to take into account the vena contracta cross section and the additional frictional losses and viscosity and turbulence effects. The numerical values of F_a are based on experimental data and are tabulated in ISO5167 [19]. For incompressible flow the coefficient F_a can be set equal to 1, while for gas and steam $F_a>1$ and it depends on the flow meter geometry and on flow conditions.

The Venturi used to perform the present analysis has been designed to operate in both fluid direction (symmetrical flow meter), with the angle of the convergent section equal to the divergent section angle (θ=21°), in order to be able to work in reverse flow conditions. The selected material, Plexiglas, allows the direct flow visualization along the instrument. Compared with the Herschel model the present VFM is characterized by a higher divergent angle (usually set to 15°), with lower manufacturing costs but also higher irreversible pressure drops, due to the flow separation.

The geometrical characteristics of the experimented VFM are described in Table 1 while the instrument is shown in Figure 1.

VFM Characteristics		
D_1	80	mm
D_2	40	mm
β	0.5	-
$\theta_{convergent} = \theta_{divergent}$	21	°
$L_{tot\_Venturi}$	340	mm
$L_{upstream}$	628	mm
$L_{downstream}$	628	mm

Table 1: VFM Characteristics

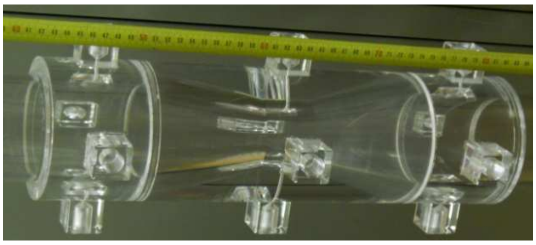

Figure 1: Venturi Flow Meter

The instrument single-phase behavior has been analyzed, as it is shown in Figure 2, in order to obtain the VFM discharge coefficient C_d (equation 2) by using the experimental values of mass flow rate and pressure, and by adopting F_a and Y equal to one.

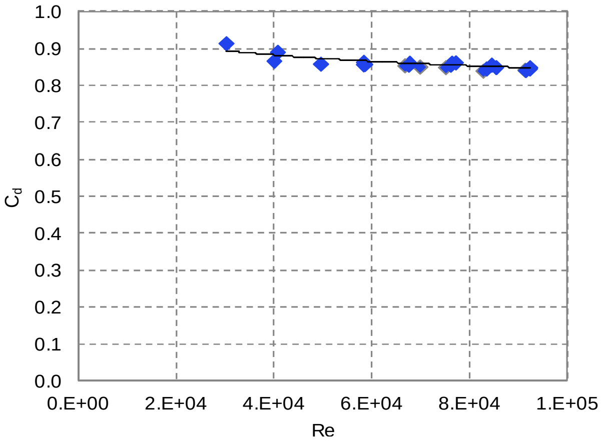

Figure 2: Experimental single phase discharge coefficient

The Reynolds number dependency can be approximated by an exponential law of type:

$$C_d = a \cdot \mathrm{Re}^b \tag{3}$$

with the parameters a and b obtained from the experimental data (a=1.5054 and b=-0.0510).

The Re number is evaluated as:

$$\mathrm{Re} = \frac{\rho V D_1}{\mu} \tag{4}$$

In single-phase flow the discharge coefficient value takes into account the phenomena of the wall flow detachment at the inlet of the divergent section; in two-phase flow, the presence of the interface between the two phases complicates the physical interpretation of this correction coefficient.

VFM TWO-PHASE FLOW MULTIPLIER

According to the well known approach [1,5-9], the frictional pressure gradient of a two-phase mixture flowing in a pipe can be correlated to the single-phase pressure drop by means of the two-phase flow multiplier:

$$\frac{\left(-\frac{dp}{dz}\right)_{TP}}{\left(-\frac{dp}{dz}\right)_g} = \phi_g^2 \tag{5}$$

where $-(dp/dz)_g$ is the frictional gas pressure gradient obtained by using the actual air phase flow rate for the two-phase flow . The two-phase flow multiplier is expressed as a function of the Martinelli parameter [1,2]:

$$\chi^2 = \frac{\left(\frac{dp}{dz}\right)_l}{\left(\frac{dp}{dz}\right)_g} \tag{6}$$

defined as the ratio between the single-phase liquid and gas pressure gradients that are evaluated with the actual flow rates, W_l and W_g for the two-phase flow.

Assuming that the two phases are flowing under turbulent regime and using the Blasius correlation for the single-phase friction factor coefficients calculation

$$f = 0.0079/Re^{1/4} \tag{7}$$

the parameter χ^2 can be written as:

$$\chi^2 = \left(\frac{1-x}{x}\right)^{0.875} \cdot \left(\frac{\rho_g}{\rho_l}\right)^{0.5} \cdot \left(\frac{\mu_l}{\mu_g}\right)^{0.125} \tag{8}$$

For a two-phase mixture flowing in orifice and Venturi devices, the parameter is usually written in the following form:

$$\chi^2_{\mathrm{mod}} = \left(\frac{1-x}{x}\right) \cdot \left(\frac{\rho_g}{\rho_l}\right)^{0.5} \tag{9}$$

The two-phase pressure drops are then related to the two-phase flow multiplier, by means of empirical or semi-empirical correlations.

Chisholm [8], for the calculation of the two-phase flow multiplier, proposed the correlation expressed as:

$$\left(\phi_g{}^2\right)_C = 1 + C\chi_{\mathrm{mod}} + \chi^2_{\mathrm{mod}} \tag{10}$$

where

$$C = \frac{1}{S}\left(\frac{\rho_l}{\rho_g}\right)^{0.5} + S\left(\frac{\rho_g}{\rho_l}\right)^{0.5} \tag{11}$$

and S is the *slip ratio* that is assumed equal to:

$$S = \left(\frac{\rho_l}{\rho_g}\right)^{1/4} \tag{12}$$

Murdock [9], following the same approach, proposed:

$$\left(\phi_g{}^2\right)_M = \left(1+1.26\chi_{\mathrm{mod}}\right)^2 \tag{13}$$

for an orifice, and

$$\left(\phi_g{}^2\right)_M = \left(1+5\chi_{\mathrm{mod}}\right)^2 \tag{14}$$

for a Venturi.

TEST SECTION AND INSTRUMENTATION

The experimental facility consists of the feed water and the feed air loops, that are equipped with instruments to measure the single-phase flow parameters (flow meter, temperature and pressure), and of a vertical pipe (having a length of about 4 m and an inner diameter of 80 mm), containing the test section. The water flow rate is changed by varying the pump rotation frequency and it is measured by a rotameter. The air flow is provided by a blower, that allows us to obtain high flow rate at low pressure (near ambient pressure), and it is measured by a calibrated orifice flow meter; whose accuracy is 2% full scale value.

The test section, shown in Figure 3, is transparent (Plexiglas) in order to visualize the flow pattern. Air enters axially into the test section and water flow is injected co-axially by means of a porous bronze; the mixing zone is located at 400 mm from the test section inlet.

The 2.5 m long test section is equipped with two pneumatic quick closing valves (QCV) to measure the volumetric void fraction; the uncertainty associated with the void fraction measurement has been estimated as $\Delta\alpha = \pm\ 0.0012$.

Downstream of the upper valve the two phases are separated in a tank at atmospheric pressure.

In the test section an Electrical Capacitance Probe (ECP), having a total length of 1210 mm, used for void fraction measurement, is installed. The ECP results have been presented in ref. [20]. After the ECP the VFM is installed between two straight pipes of 1290 mm upstream and downstream respectively. The absolute pressure is measured at the inlet of the test section, while the VFM pressure drops are measured between the inlet and the throat sections and between the inlet and the outlet sections (irreversible pressure loss). The distance between the inlet and outlet sections pressure taps (Figure 1) is 320 mm. The fluid temperature is measured at different location of the test section by means of thermocouples.

The mixture void fraction is measured by means of the QCV technique. The instrument signals (single phases parameters and signals from the test section instrumentation) are acquired by means of a NI DAQ, using the LabView® software. The acquisition time was equal to 30 s with an acquisition frequency of 1250 Hz.

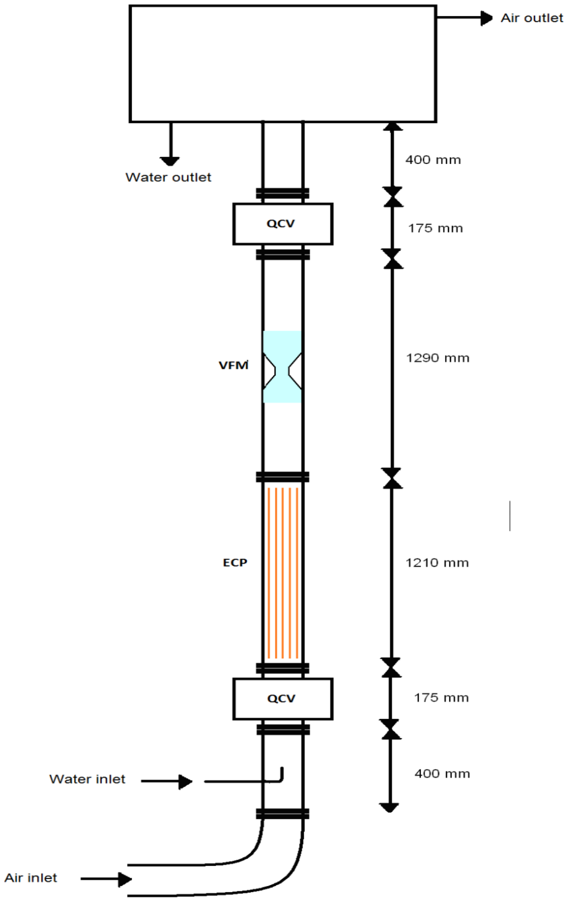

Figure 3: Vertical Test Section schematic

EXPERIMENTAL MATRIX

The experiments have been carried out fixing the mass flow rate of the two phases at the inlet of the test section.

The air superficial velocity ranged between 14 and 18 m/s while the water superficial velocity ranged between 0.0008 and 0.005 m/s, so that the flow pattern was annular and the corresponding void fraction is higher than 0.97, while the flow quality ranges from 0.78 to 0.96.

For the tested superficial velocities range the variation of the void fraction (measured by QVC technique) is shown in Figure 4. The small variation of this parameter is due to the very small values of the liquid superficial velocities. In the present work the value of $\rho_l J_l$ is much smaller than $\rho_g J_g$. The liquid superficial velocity range has been chosen in order to obtain the annular flow pattern in the test section; considering the experimented air flow velocites, higher values of the liquid superficial velocities involve the presence of a count-current flow.

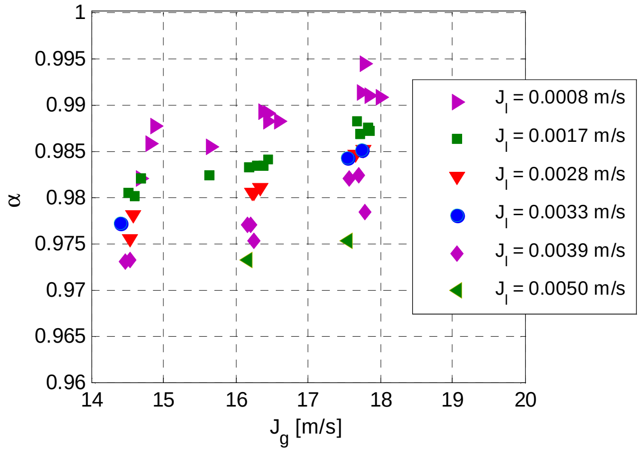

Figure 4: Void fraction as a function of the superficial velocity of the two-phases

EXPERIMENTAL VENTURI FLOW METER BEHAVIOR IN TWO-PHASE FLOW

In Figures 5 and 6 the experimental VFM pressure drops are plotted as a function of the flow conditions.

In Figure 5 the pressure drop dependency on the total mass flow rate is shown: the VFM pressure drop is a function of the mass flow rate of the two phases; introducing the ratio W_l/W_g, if this ratio is equal to zero the air single phase flow is obtained, while increasing the fraction of water in the mixture an increase of the pressure drops is highlighted. The dependency on the superficial velocities of the two phases and the small effect due to the liquid flow rate is confirmed in Figure 6. In Figure 7 the two-phase pressure drop, normalized with reference to the gas single-phase pressure drop, is shown as a function of the gas superficial velocity: the two-phase flow value is very close to the gas single-phase flow value, with a maximum increase of about 7%.

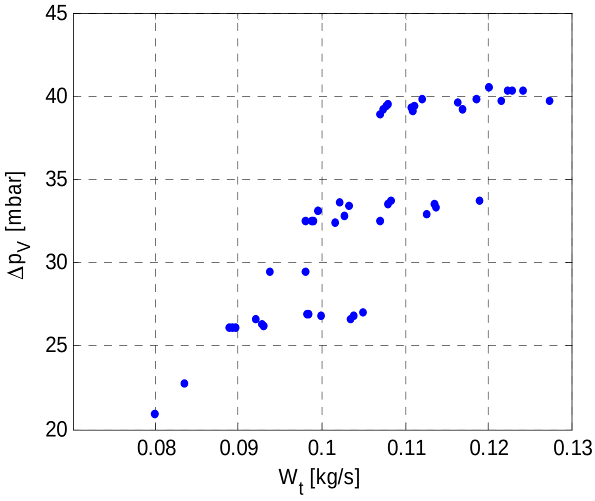

Figure 5: VFM pressure drop as a function of the total mixture mass flow rate

The pressure drop increase in presence of two–phase flow is caused by the interaction between the gas and liquid phases: liquid droplets accelerated by the gas, irreversible drag force work done by the gas phase accelerating the liquid film and frictional wall losses, determine the magnitude of the observed pressure drop increase. The flow field is characterized and complicated by the continuous deposition and entrainment of liquid droplets along the Venturi length and by the presence of waves on the liquid film surface. The continuous deposition and entrainment process contributes to the overall pressure drop through the loss of momentum caused by the acceleration of the newly entrained droplets.

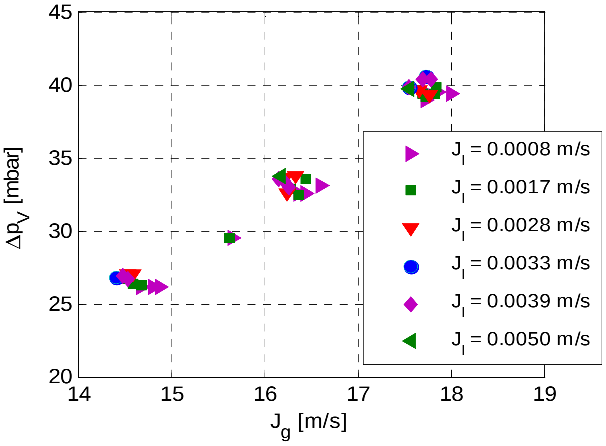

Figure 6: VFM pressure drop as a function of the two phases superficial velocities

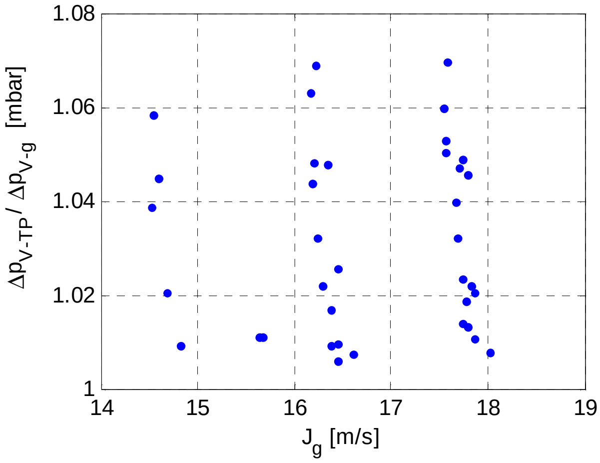

Figure 7: Normalized VFM pressure drop as a function of gas superficial velocity

The surface waves produce an effectively roughened surface over which the gas flows increasing the momentum loss due to the interfacial shear stress. On the ground of the previous considerations, the pressure drop in the VFM can be expressed as a function of the single-phase pressure drop with a correction factor (a two-phase flow multiplier) that can take into account the presence and the effect of the liquid phase at different flow qualities. The two-phase flow multiplier can been written as:

$$\phi^2_{g,\mathrm{mod}} = 7.8\cdot\chi+1 \tag{15}$$

where the two constants have been obtained as best-fit of the present experimental data.

The two-phase flow multiplier values evaluated by the correlation (15) are compared with the correlations of Murdock, Chisholm and the present test data (Figure 8): the classical correlations under estimate the two-phase multiplier ϕ^2_g.

The experimental points dispersion can be justified by a change of the slip ratio value, that is considered constant in all the analyzed correlations. In Figure 9 the pressure drops evaluated with the new correlation are compared with the experimental values, showing a very good agreement and a calculation accuracy better than 5%.

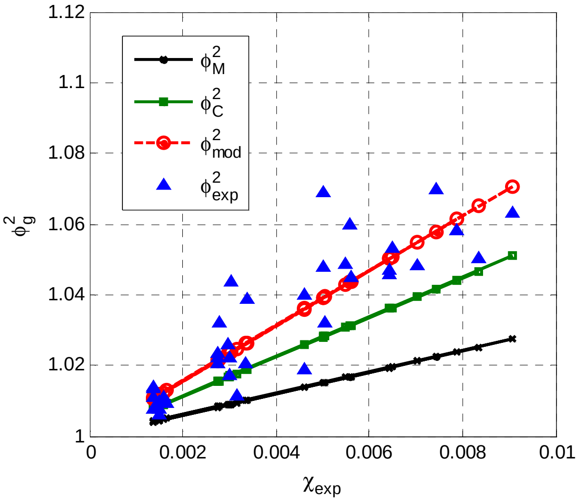

Figure 8: Two- phase flow multiplier: comparison between experimental data and correlations

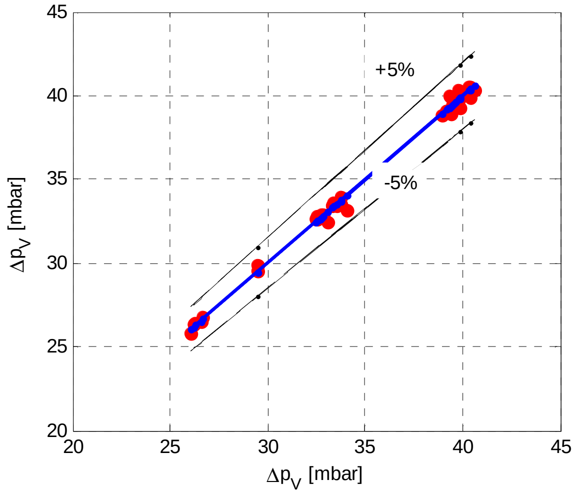

Figure 9: VFM pressures drops: comparison between experimental data and predicted values (equation 15)

In the present work also the irreversible pressure losses, measured between the Venturi inlet and outlet sections have been analyzed and correlated with the flow parameters. In the following pictures the dependency of the VFM irreversible pressure loss on the flow parameters is highlighted. The analysis of this component, that usually are not considered in two-phase flow models, allows us to understand better the effect of the dispersed phase in the two- phase pressure drops.

In Figure 10 the two VFM pressure drop components are shown as a function of the total mixture mass flow rate.

Figure 11 shows the irreversible pressure loss component with the pressure drop component measured between VFM inlet and throat sections. The circle points highlight the linear relation existing between inlet-outlet (irreversible component) and inlet-throat pressure drops in single-phase flow. The square points show that for an annular flow the relation between the two pressure components is not longer linear; the difference is clearly due to the liquid phase presence, so that the relation between the two components can be used to analyze the effect of the liquid flow rate and to estimate the liquid mass flow rate itself.

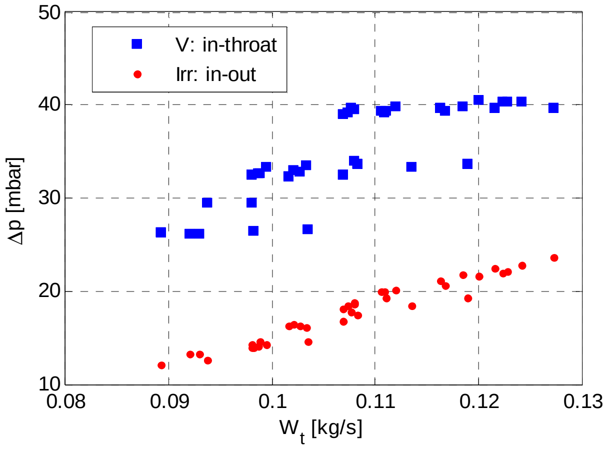

Figure 10: VFM pressure drop and VFM irreversible pressure loss vs. total mass flow rate

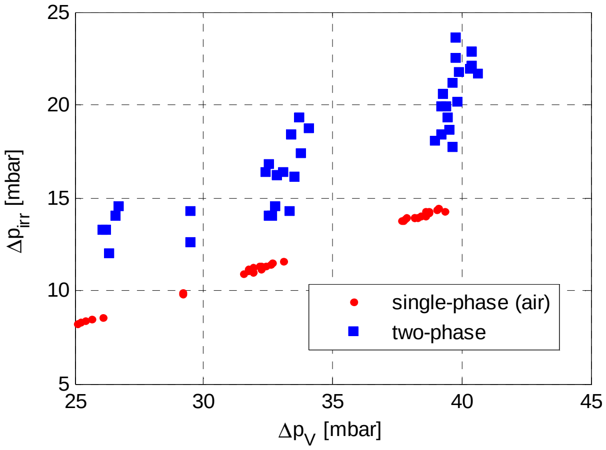

Figure 11: VFM irreversible pressure loss vs. VFM pressure drops

Figures 12 shows the dependency of the irreversible pressure loss on the superficial velocities of the phases. In Figure 13 the two-phase irreversible pressure loss is plotted as a function of the irreversible single-phase (air) component.

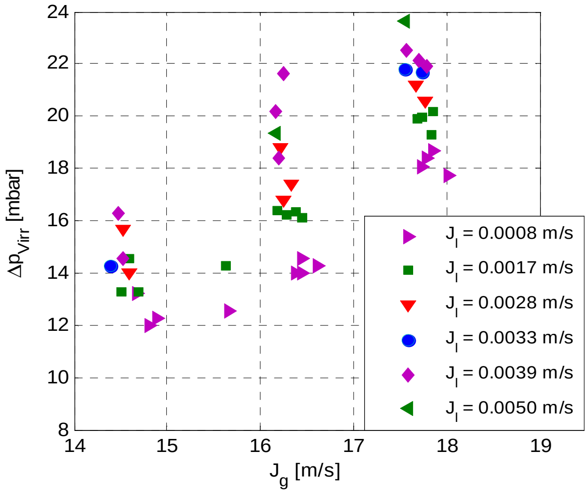

Figure 12: VFM irreversible pressure loss as a function of the superficial velocities of air and water

While, due to the liquid phase presence, the inlet-throat pressure drop increases of about 10%, if compared to the single-phase flow, the irreversible pressure loss increases from about 20% to 100% depending on the liquid flow rate.

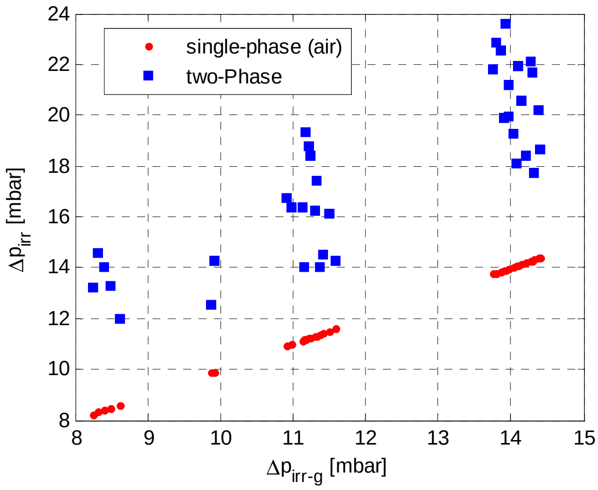

Figure 13: VFM pressure loss as a function of the air single-phase irreversible pressure loss

The previous analysis allows the derivation of a correlation able to describe the irreversible pressure loss change as a function of the flow rate of the two phases. The proposed correlation, developed for the present tested conditions, expresses the irreversible pressure loss as a function of the gas superficial velocity and of the ratio between the liquid and the gas superficial velocities, highlighting the effect of the dispersed phase:

$$\Delta p_{irr} = k_1 \cdot \left(\rho_g J_g^{k_2}\right) \cdot \left(J_l / J_g\right)^{k_3} + k_4 \qquad (16)$$

where J_g and J_l are the superficial velocity of air and water respectively. The following constants have been obtained from the best fit of the experimental data:

k_1 = 0.2096
k_2 = 2
k_3 = 0.13
k_4= -2.9786

The comparison between the predicted irreversible pressure loss and the test data is shown in Figure 14: the proposed correlation allows the estimation of the VFM irreversible pressure loss, in annular flow, at high void fraction, with an accuracy of 5%.

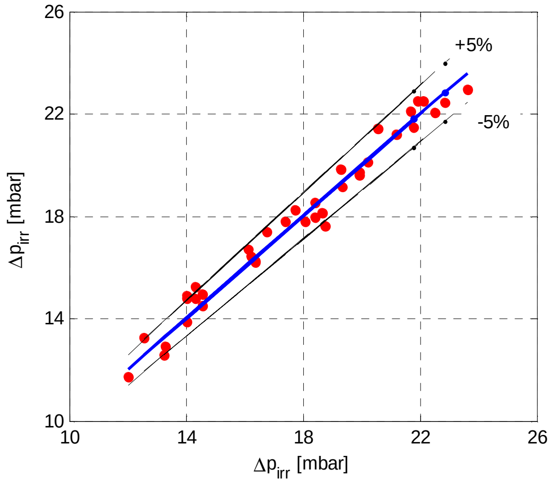

Figure 14: Comparison between predicted (equation 16) and experimental VFM irreversible pressure losses

TWO-PHASE MASS FLOW RATE EVALUATION

The measurement of the two-phase flow mass flow rate is essential for several industrial applications.

Typically a set of instruments (Spool Piece - SP) must be installed in order to evaluate the mass flow rate of the phases in a large range of flow patterns, pressures and temperatures [6,7]. Each instrument of the SP has to be sensitive to the different properties of the flow (like momentum, velocity, density, void fraction) and the selection of the instruments depends strongly on the experimental conditions: pressure, temperature and phases velocities. Different instruments can be coupled in a SP, and the VFM, characterized by the absence of moving parts and by a smoother flow profile than the orifice plates, is one of the instruments more suitable to be installed in a wide range of industrial applications.

In single-phase flow the VFM allows the estimation of the mass flow rate from the pressure drop across the pipe restriction, but in presence of two phases the direct correlation between pressure drops and mass flow rate is not possible, so that additional information and a model able to interpret the signals are required [21]-[23].

In limited application ranges, if the flow pattern doesn't change, as in the present experimental conditions, it is possible to extract the essential information from the signals of a VFM.

The closure equation of the model in this case is based on the measurement of the irreversible pressure losses and on the proposed correlation (16).

Using an iterative approach the flow quality and the mass flow rate of the two phases have been estimated by using only the acquired signals of the VFM and the information concerning the absolute pressure and the temperature of the flow. The flow quality is evaluated using the correlation (15): an initial guess value of the parameter is used to evaluate the VFM pressure drops, and the iterative loop goes on until the estimated pressure drop reaches the experimental value. Then the mass flow rates of the two phases are estimated by using the flow quality value and the correlation (16). The reference signals have been obtained as the mean values of the 30 s acquisition time. In Figure 15 the estimated flow quality values are compared with the experimental data, obtained from the measurement of the single phases mass flow rate. The relative error is in each case lower than 5%.

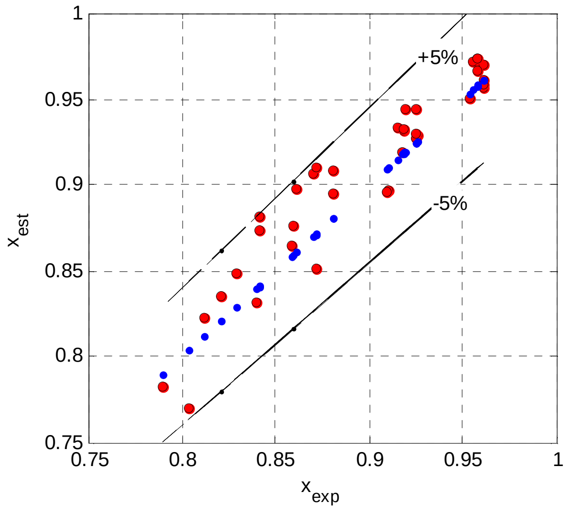

Figure 15: Comparison between experimental and estimated flow quality

In Figures 16 and 17 the estimated mass flow rates of air and water are compared with the measured values: the air mass flow rate is estimated with an accuracy of 2%, while a lower accuracy characterizes the liquid flow rate prediction (the relative error is lower than 30% for all conditions): the standard deviations are 1%, 10 % and 2 % for the air flow rate, the liquid flow rate and the quality respectively.

CONCLUSIONS

In the present research work, the experimental investigation of a vertical upward annular two-phase flow in a Venturi Flow Meter (VFM) has been performed. The dependency of the pressure drops, evaluated between the VFM inlet and throat and between the inlet and outlet sections (irreversible pressure loss), on the characteristic flow parameters (flow velocities, quality and void fraction) have been analyzed and discussed.

Correlations describing the relation between velocities and VFM pressure drops have been proposed for the two pressure drops components. For both correlations, the prediction error is lower than 5%.

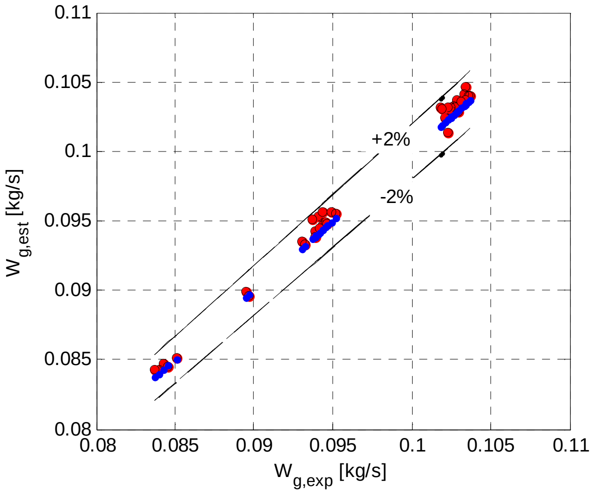

Figure 16: Comparison between experimental and estimated air single-phase mass flow rates

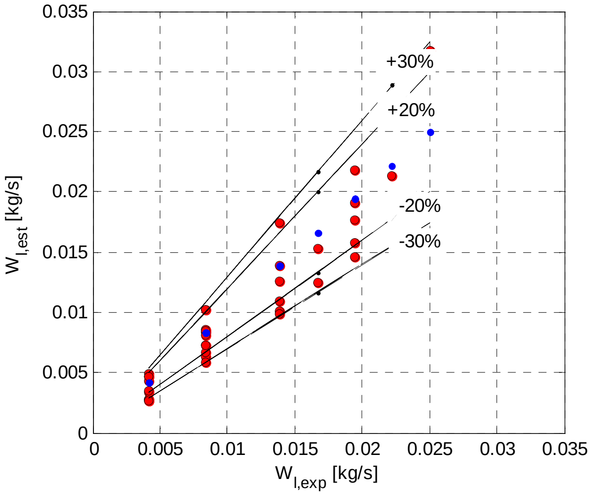

Figure17: Comparison between experimental and estimated water single-phase mass flow rates

The paper highlights that, from the measurement of the VFM irreversible pressure losses, important information can be extracted concerning the effect of the liquid dispersed phase on the total pressure drops. Due to the liquid phase presence, the inlet-throat pressure drop increases of about 10% compared to the single-phase flow, while the irreversible pressure losses increase from about 20% to 100% depending on the liquid flow rate. The proposed correlation describes the irreversible pressure loss change as a function of the flow rate of the two-phases, highlighting the effect of the dispersed phase.

In addition, the possibility to derive the mass flow rate of the two phases from the instrument signals has been analysed. The developed model allows the evaluation of the flow quality of the mixture with an accuracy of 5% and the estimation of the mass flow rate of air and water with an accuracy of 2% and 30% respectively (the standard deviations are 1%, 10 % and 2 % for the air flow rate, the liquid flow rate and the quality respectively).

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