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MASS FLOW RATE MEASUREMENTS IN GAS-LIQUID FLOWS BY MEANS OF A VENTURI OR ORIFICE PLATE COUPLED TO A VOID FRACTION SENSOR

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ABSTRACT

Two-phase flow measurements were carried out using a resistive void fraction meter coupled to a venturi or orifice plate. The measurement system used to estimate the liquid and gas mass flow rates was evaluated using an air-water experimental facility. Experiments included upward vertical and horizontal flow, annular, bubbly, churn and slug patterns, void fraction ranging from 2% to 85%, water flow rate up to 4000 kg/h, air flow rate up to 50 kg/h, and quality up to almost 10%. The fractional root-mean-square (RMS) deviation of the two-phase mass flow rate in upward vertical flow through a venturi plate is 6.8% using the correlation of Chisholm (1967). For the orifice plate, the RMS deviation of the vertical flow is 5.5% using the correlation of Zhang *et al*. (2005). The results show that the flow direction has no significant influence on the meters in relation to the pressure drop in the experimental operation range. Quality and slip ratio analyses were also performed. The results show a mean slip ratio lower than 1.1, when bubbly and slug flow patterns are encountered for mean void fractions lower than 70%.

1. INTRODUCTION

For the oil and gas industry, the measurement of mass flow rate in real time without separating the phases is desirable in order to reduce costs, increase production and reach excellence in oil and gas transport. The requirement for precise measurements has motivated considerable research studies [1,2,3].

According to Falcone *et al.* [1], flow measurements without separating the phases can reduce the amount of industrial machinery, such as the exclusive lines to test separators found in the wells, and, thus, reduce space requirements and costs. Steven [2] considers that several test separators are undersized and present multiphase flow in situations where single-phase flow would be expected. In numerous gas fields, natural gas reserves have reached the last stages of their production, and, therefore, the gas flow has became a mixture of gas and liquid since heavy hydrocarbons condensate due to the reduced pressure and changes in the well conditions.

This scenario has promoted the search for appropriate gas, oil and water flow rate measurements in the wells. Measurement facilities are especially useful in deepwater operations and low cost and precise meters are required, besides viable technologies and practical solutions for measurement operations.

Common techniques for measuring multiphase flows employ a combination of different measuring tools [4]. It is common to find differential pressure devices associated with other kinds of meters, such as void fraction sensors. Recently, gas-liquid flow research by means of a differential pressure device and a void fraction sensor has been reported in [5], [6] and [7]. Zhang *et al.* [5] measured air-water mass flow rates with orifice and void fraction meters, [6] measured refrigerant R-134a liquid-vapor mass flow rates with venturi and void fraction meters and Zhang *et al.* [7] developed correlations for measuring oil-gas mass flow rates through venturi and using electrical capacitance tomography.

The aim of this research is to estimate the mass flow rates in a gas-liquid two-phase flow through a measurement system consisting of an impedance void meter of the non-intrusive resistance type, coupled to a venturi or orifice plate flow meter. Two-phase flow correlations were tested, and the experimental quality and slip ratio factor were analyzed. A comparison between the performance of an orifice plate and a venturi in gas-liquid flow was carried out.

2. LITERATURE REVIEW

Adiabatic steady-state two-phase flow fundamentals are reviewed in this section. Average properties were assumed for the fluids. The subscripts l and g are related to the liquid and gas properties, respectively.

In a single-phase flow, rearranging the Bernoulli, continuity and energy equations, and introducing a theoretical correction coefficient, C_d , known also as the discharge coefficient, it is possible to correlate the mass flow rate, m, to the pressure drop, Δp, across a differential pressure device by:

$$m = \frac{C_d A Y F_a}{\sqrt{1-\beta^4}} \sqrt{2\rho \Delta p} \quad (1)$$

where A, β, ρ, C_d, Y, and F_a represent the venturi throat or the orifice area, the throat (or orifice) diameter to pipe diameter ratio, the fluid density, the discharge coefficient, the compressibility coefficient and the thermal expansion correction factor, respectively. Neglecting the thermal effects and considering an incompressible flow, Y and F_a are equal to 1. The discharge coefficient, C_d, as always, is a function of the Reynolds number, Re_D, and is dependent on the differential pressure meter type.

Based on the single-phase flow equation, a mechanical method to predict flow rates was used, implementing semi-empirical two-phase flow correlations found in the literature for low quality flows. To take into account the two-phase flow occurrence, Zhang *et al.* [5] suggested the introduction of the K_L parameter into Eq. (1) to summarize the necessary corrections for correlating the two-phase mass flow rate, m_{TP}, to the two-phase pressure drop, Δp_{TP},

$$m_{TP} = \frac{C_{d,TP} A Y_{TP} F_a}{\sqrt{1-\beta^4}} K_L \sqrt{2\rho_l \Delta p_{TP}} \tag{2}$$

where $C_{d,TP}$ and Y_{TP} represent the two-phase discharge and two-phase compressibility coefficients, respectively. It was considered that Y_{TP}=1 for Mach numbers lower than 0.3. The K_L parameter is dependent on the two-phase flow correlation. In general, this parameter is a function of the quality or void fraction and the densities of the fluids. The appearance of the liquid density in Eq. (2) is related to the low quality flow.

The slip ratio factor, S, is defined by [8,9] as the ratio between the mean gas and liquid velocities, Eq. (3).

$$S = \frac{v_g}{v_l} = \frac{\rho_l}{\rho_g} \frac{x}{(1-x)} \frac{(1-\alpha)}{\alpha} \tag{3}$$

In sequence, the homogeneous model and the correlations of [5], [7] and [10] are presented below. All of them are given in the form proposed by [5].

2.1 Homogeneous Model

The homogeneous model treats a two-phase flow as a pseudo-fluid. The slip ratio is equal to unity. Its development can be observed in [8] and [9].

Rearranging the homogeneous model according to Eq. (2), the K_L parameter can be obtained by Eq. (4).

$$K_L = \sqrt{\frac{1}{x\left(\frac{\rho_l}{\rho_g} - 1\right) + 1}} \tag{4}$$

2.2 Chisholm (1967)

Chisholm [10] developed a two-phase flow correlation, considering the slip between the fluids. It was assumed to be an incompressible two-phase flow, with negligible upstream momentum, no phase change, irrelevant drag forces in the wall when compared to the interfacial forces between the phases, and a constant void fraction across the differential pressure device. Chisholm's correlation is defined by

$$\Delta P_{TP} = \Delta P_l + C\sqrt{\Delta P_l \Delta P_g} + \Delta P_g$$

(5)

where C is an empirical coefficient, Δp_l the pressure drop if only liquid flows, and Δp_g the pressure drop if only gas flows. C is defined by

$$C = \frac{1}{S}\sqrt{\frac{\rho_l}{\rho_g}} + S\sqrt{\frac{\rho_g}{\rho_l}} \tag{6}$$

Chisholm [11] proposed a procedure to evaluate the slip ratio and, indirectly, the coefficient C by means of steam-water flow data obtained for orifice plates. The author used the Lockhart-Martinelli parameter, X, as defined by [9], as a criterion for estimating the slip ratio. For $X \geq 1$, Eq. (7) is provided, and for $X<1$, Eq. (8).

$$S = \left(1 + x\left(\frac{\rho_l}{\rho_g} - 1\right)\right)^{1/2} \tag{7}$$

$$S = \left(\frac{\rho_l}{\rho_g}\right)^{1/4} \tag{8}$$

The Lockhart-Martinelli parameter was firstly defined as the square root of the liquid and gas pressure drop ratio due to friction. Some correlations have made use of this parameter to predict the two-phase flow pressure drop or two-phase mass flow rate. However, the parameter is utilized with a modification to the original meaning as observed by [2]. At this point, it is defined by Eq. (9) as the square root of the liquid and gas pressure drop ratio due to acceleration.

$$X = \frac{\sqrt{\Delta P_l}}{\sqrt{\Delta P_g}} = \left(\frac{1-x}{x}\right)\frac{\sqrt{\rho_g}}{\sqrt{\rho_l}} \tag{9}$$

Combining Equations (5), (6) and (9), and according to Eq. (2), it is possible to obtain

$$K_L = \left(\frac{1}{1-x}\right)\left[1 + \left(\frac{\frac{1}{S}\sqrt{\frac{\rho_l}{\rho_g}} + S\sqrt{\frac{\rho_g}{\rho_l}}}{\left(\frac{1-x}{x}\right)\frac{\sqrt{\rho_g}}{\sqrt{\rho_l}}}\right) + \left(\frac{1}{\left(\frac{1-x}{x}\right)^2 \frac{\rho_g}{\rho_l}}\right)\right]^{-\frac{1}{2}} \tag{10}$$

2.3 Zhang *et al.* (1992)

Zhang *et al.* (1992) researched low quality (x<1%) air-water flow through orifice plates. These authors proposed a correlation to obtain the two-phase mass flow rate as defined by Eq. (11).

$$K_L = \left\{\left[x^{\left(1.25+0.25x^{1/3}\right)}\right]\left(\frac{\rho_l}{\rho_g} - 1\right) + 1\right\}^{-\frac{1}{2}} \tag{11}$$

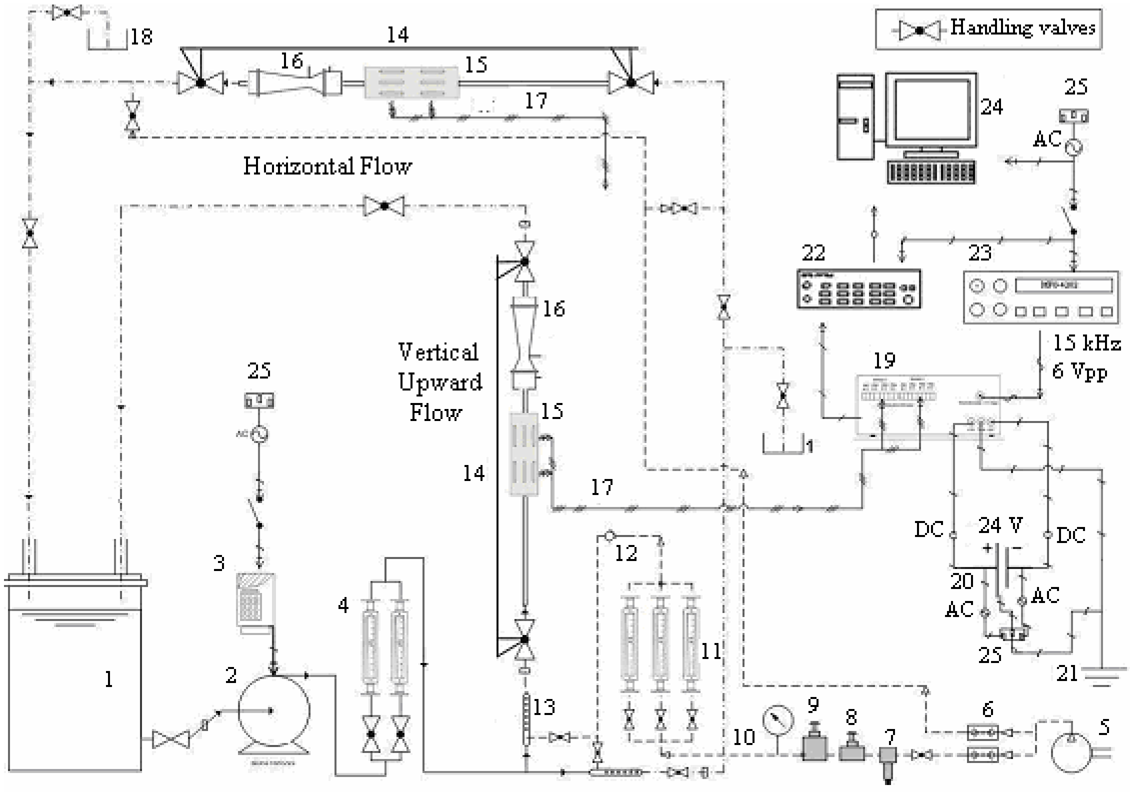

Fig. 1 - Scheme of the air-water two-phase loop

1 – Water tank; 2 – Water pump; 3 – Frequency inverter; 4 – Rotameters; 5 – Air compressor; 6 – Air entrances; 7 – Air filter; 8 – Air flow control valve; 9 – Air pressure control valve; 10 – Manometer; 11 – Rotameters; 12 – One-way valve; 13 – Air-water mixer; 14 – Quick closing valves; 15 – Electrodes; 16 – Venturi or orifice plate; 17 – Coaxial cable; 18 – Water tank; 19 – Electronic circuit ; 20 – AC/DC power supply ; 21 – Ground ; 22 – Multiplexer; 23 – Voltage function Generator; 24 – PC; 25 – Electrical grid

2.4 Zhang *et al*. (2005)

Recently, Zhang *et al*. [7] researched low quality (x<2%) oil-air flow through a venturi. These authors measured the void fraction by means of tomography. They proposed semi-empirical correlations to predict m_{TP}, Eq. (12), and x, Eq. (13), through modifications to the homogeneous model. They attempted to include the influence of the slip ratio by means of constants.

$$K_L = \left[c \left(\frac{\alpha}{1-\alpha} \right)^n \left(\frac{\rho_l}{\rho_g} \right)^m + 1 \right]^{-\frac{1}{2}} \quad (12)$$

$$x = c' \left(\frac{\alpha}{1-\alpha} \right) \left(\frac{\rho_g}{\rho_l} \right)^H \quad (13)$$

where c, n, m, c', and H are constants which are dependent on the flow regimes and on the test conditions. For bubbly and slug flow, they are equal to 0.50, 0.95, 0.02, 0.51 and 0.65, respectively.

3. EXPERIMENT

3.1 Experimental Setup

Experiments were carried out in an air-water two-phase loop, as shown in Fig. 1, installed at the LEPTEN/Boiling laboratory, Department of Mechanical Engineering, Federal University of Santa Catarina, Brazil. A water pump and an air compressor were used in order to obtain a wide range of flow patterns, annular, bubbly, churn and slug regimes, in a gas-liquid concurrent flow, including measurements in the upward vertical and horizontal directions.

Before the fluids were mixed, the flow rates were measured by rotameters. Water mass flow rates of up to 4000 kg/h and air mass flow rates up to 50 kg/h were used. Pressure in the control volume ranged from 2 to 3 bar, void fraction from 2 to 85% and the quality used was up to almost 10%. As will be described later, all measured points were used to analyze the slip ratio and quality, but not all of them were used to investigate the two-phase mass flow rate.

Prior to the main tests, a resistive void fraction sensor was calibrated by means of quick closing valves, as can be seen in [14]. After the void fraction sensor calibration, tests with a venturi and an orifice plate with corner taps were carried out in the horizontal and upward vertical direction. The pipe inner diameter, D, was 21 mm and the throat (or orifice) diameter to pipe diameter ratio was 0.5. The electrodes of the void fraction sensor were located at a distance of 75 D from the last section change, and the flow meters, venturi or orifice plate, were located at a distance of 95 D.

3.2 Experimental Procedure

To provide the necessary information on the two-phase flow characteristics, thermocouples, an absolute pressure transducer and a resistive void fraction sensor were used to obtain the pressure and temperature and, consequently, the densities of the fluids, and the void fraction. Also, a differential pressure transducer located downstream of the void fraction sensor was used to obtain extra information to estimate the flow rates. Figure 2 shows the measurement system scheme.

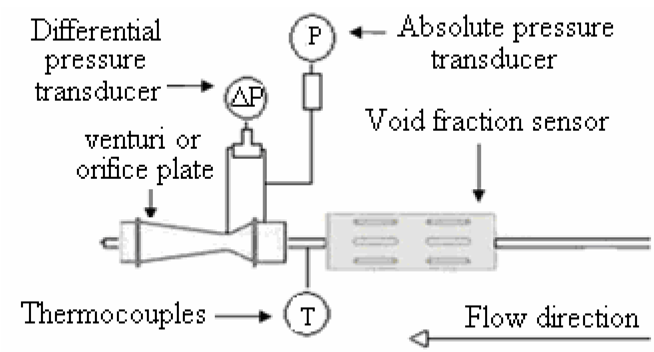

Fig. 2 - Measurement system scheme

Based on the variables obtained using the sensors, the semi-empirical models given in the above sections and the slip ratio definition, Eq. (3), Fig. 3 presents a flow map showing the chosen path to predict the flow rates.

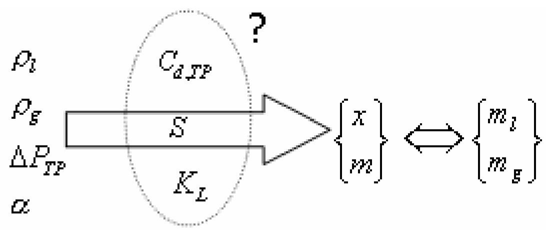

Fig. 3 - Experimental procedure flow map

Considering incompressible flow and neglecting the thermal effects, it is necessary to determine a further three parameters: K_L , S and $C_{d,TP}$. The K_L parameter is dependent on the two-phase flow correlation and, in general, it is a function of the densities of the fluids and void fraction or quality.

Under specific conditions, it is possible to consider the slip ratio factor, S, to be close to unity. This non-slip condition (S=1) is stated by [13] as being reasonable for the bubbly pattern, when small bubbles are encountered.

According to [5] and [12], for low quality gas-liquid flows (considering x<1%), $C_{d,TP}$ is a function of the Reynolds number for the liquid flow, $Re_{D,l}$. According to ISO 5167-1, the discharge coefficient for the applied meters, venturi and orifice plate with corner taps, can be approximated to the constants 0.98 and 0.61, respectively, for $Re_{D,l}$ >30,000. Details of the meters used are given in [14].

4. RESULTS AND ANALYSIS

A total of 260 experimental data points were obtained. The data for upward vertical flow are represented in Fig. 4, on a Hewitt and Roberts (1969) map, and those for horizontal flow are represented in Fig. 5, on a Baker (1954) map, as reported by Carey (1992). According to [8] and [13], these maps plausibly characterize the water and air two-phase flow under low pressure operation conditions. Through visual observation, the validity of these maps was confirmed. Each experimental point represents five measurements for 20 s, where data were collected using a multiplexer.

On observing Figs. 4 and 5, the presence of the slug regime for the majority of the experimental points can be noted. For upward vertical flow, there are still some points in the churn and bubbly patterns. For horizontal flow, annular and bubbly patterns are also found. These figures show the experimental data set used to evaluate the quality, the slip ratio factor, the two-phase pressure drop and the two-phase mass flow rate.

It should be noted that all 260 points were used to analyze the slip ratio and quality, but only 100 points were used to analyze the two-phase pressure drop and to predict the two-phase mass flow rate. Fifty of these 100 points were obtained for each meter, venturi or orifice plate. For each meter, 25 of the 50 points were obtained for each direction, upward vertical and horizontal. The pressure drop value obtained through the experimental points represented by circles, on the left of Figures 4 and 5, contains high uncertainty levels, so it was ignored.

For the data represented by squares, values of $Re_{D,l}$ >30,000 and x <0.011 were obtained and $C_{d,TP}$ was considered to be constant as stated before.

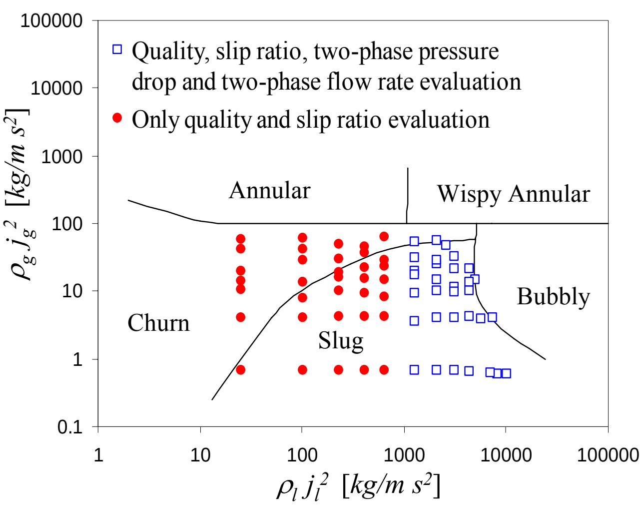

Fig. 4 - Experimental data points represented on a Hewitt and Roberts map, upward vertical flow

On the Baker map, Fig. 5, the parameters ψ and λ are equal to 1 for air-water flow.

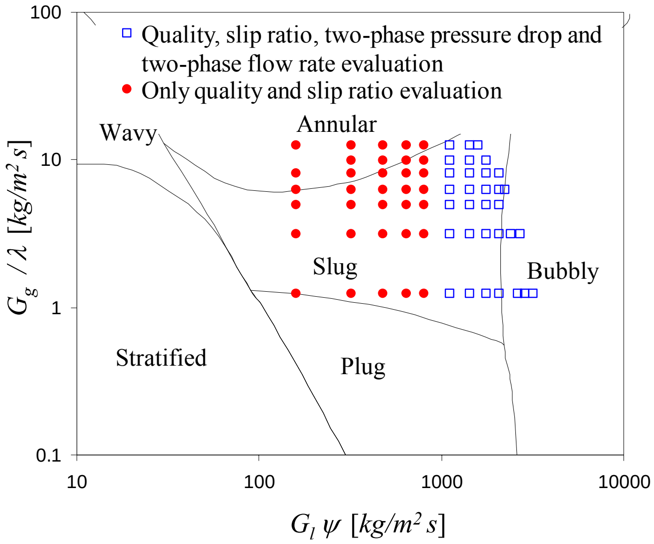

Fig. 5 - Experimental data points represented on a Baker map, horizontal flow

In order to evaluate the performance of the correlations in predicting the two-phase experimental values, the fractional root mean square (RMS) deviation was used as given by Eq. (14).

$$RMS = \sqrt{\frac{1}{N}\sum\left[\frac{y_{i,calculated} - y_{i,measured}}{y_{i,measured}}\right]^2} \qquad (14)$$

4.1 Two-phase Pressure Drop

For the same meter, venturi or orifice plate, the pressure drop measurements in the upward vertical and horizontal direction showed no significant differences as a result of disturbances in the flow due to gravity acceleration, as reported in [14].

Figures 6 and 7 show the pressure drop for horizontal flow in the venturi and in the orifice plate, respectively, as a function of the water and air mass flow rates. Since the graphs for the vertical flow are similar, they are not presented in this paper.

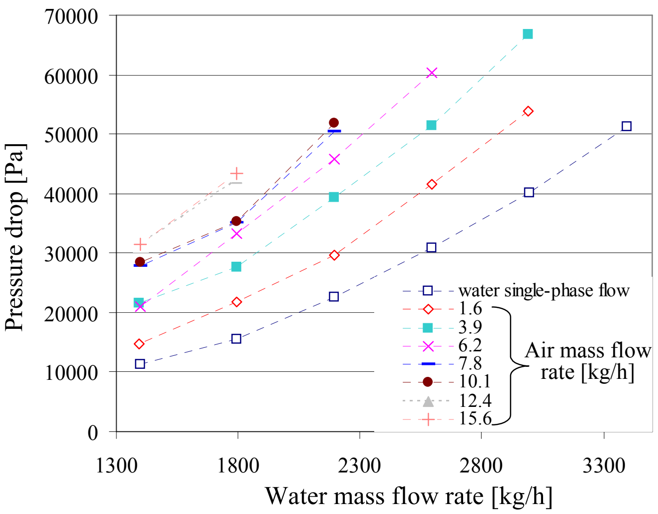

Fig. 6 - Pressure drop in the venturi, horizontal flow

Differential pressure transducer uncertainties varied from ± 2.3 to ± 3.0 kPa.

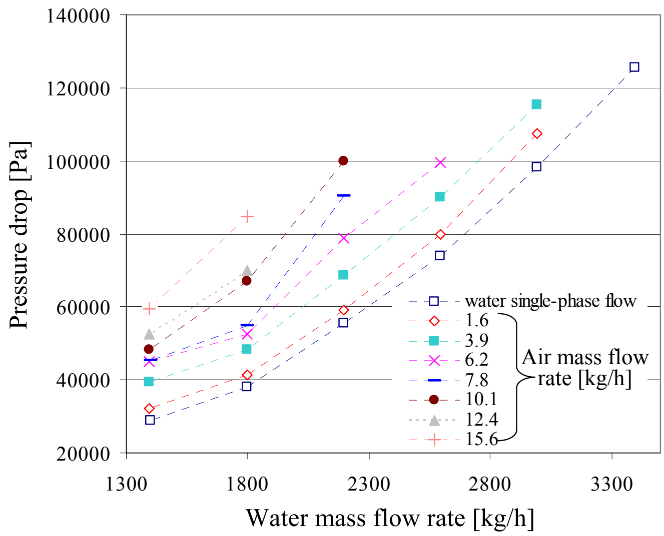

Fig. 7 - Pressure drop in the orifice plate, horizontal flow

According to the experimental results observed in these figures, even for very low qualities (x<0.011), for a fixed water mass flow rate, small enhancements in the air mass flow rate can amplify significantly the two-phase pressure drop.

For a fixed air mass flow rate, the two-phase pressure drop increased with the water mass flow rate increase. For an air mass flow rate of around 1.6 and 3.9 kg/h, the behaviors of the two-phase mass flow rate and the two-phase pressure drop were similar to the water single-phase flow behavior.

Table 1 gives the mean values for the ratio between the orifice plate and venturi pressure drops for horizontal and upward vertical flows and their mean standard deviation. Table 2 shows the mean values for the ratio between the pressure drops of the upward vertical and horizontal flows for each meter and their mean standard deviation.

Table 1 - Pressure drop ratio: the meter effect

Pressure drop ratio	Mean	Mean standard deviation
$\left.\frac{\Delta p_{OP}}{\Delta p_V}\right\|_{vertical}$	1.85	± 0.029
$\left.\frac{\Delta p_{OP}}{\Delta p_V}\right\|_{horizontal}$	1.78	± 0.037

The mean ratio between the pressure drop in the orifice plate and the pressure drop in the venturi, considering the flow in the horizontal and upward vertical directions, was 1.81.

Table 2 - Pressure drop ratio: the flow direction effect

Pressure drop ratio	Mean	Mean standard deviation
$\left.\frac{\Delta p_{vertical}}{\Delta p_{horizontal}}\right\|_{OP}$	1.02	± 0.018
$\left.\frac{\Delta p_{vertical}}{\Delta p_{horizontal}}\right\|_{V}$	0.98	± 0.012

For the same meter, the mean ratio between the pressure drop with vertical flow and that with horizontal upward flow was close to one. Asymmetries in the phase distributions caused by gravity did not influence considerably the pressure drop in the meters for slug and bubbly patterns in the horizontal and upward vertical flows.

This result is rather important, because it shows that the two-phase measurement system consisting of thermocouples, absolute and differential pressure transducers and an appropriate void fraction sensor had a good performance regardless of the flow direction, for the level of pressure, ranges of quality and mass flow rates tested in this analysis.

4.2 Slip Ratio

Figure 8 presents the experimental slip ratio as a function of the mean void fraction, including upward vertical and horizontal flows, and identification of the flow regimes according to the Baker and the Hewitt and Roberts flow maps, as indicated in Figures 4 and 5.

It can be seen that the slip ratio factor increases with the transition from a slug to annular or churn flow pattern. When these patterns are reached, the gas momentum is sufficient to throw the liquid against the walls and the gas flow may accelerate considerably. This occurred when mean void fractions over 0.7 and quality over 1% were reached. For quality close to 7%, slip ratio values close to 7 were found. Moura and Marvillet [6] obtained experimental slip ratio values close to 40, when testing a gas-liquid flow with R-134a, reaching quality values in the order of 90%.

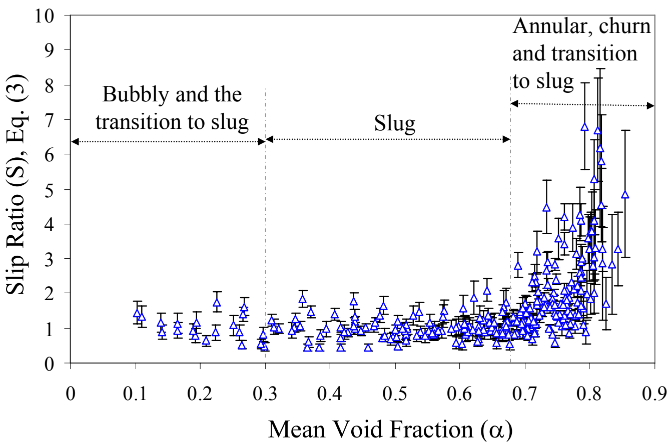

Fig. 8 - Slip ratio obtained experimentally by Eq. (3)

Table 3 gives the mean slip ratio values for the three different regions specified in Fig. 8, including the fractional RMS deviation for the non-slip condition (S =1).

Table 3 - Experimental slip ratio calculated by Eq. (3)

Void Fraction	α ≤0.3	0.3<α<0.7	α ≥0.7
Mean Slip Ratio	1.02	1.08	2.36
Fractional RMS deviation (%) for the non-slip condition (S=1)	35.1	35.4	187.6

A mean slip ratio of 1.06 was obtained for bubbly and slug patterns (α < 0.7), and thus the slip effect for these two regions was neglected in this study. Not surprisingly, the use of the homogeneous model for predictions in flow patterns other than bubbly, such as slug flow, gives reasonable results.

4.3 Quality

Figure 9 shows, in a logarithmic graph, the comparison between the experimental quality values and those predicted through Eq. (3), assuming the non-slip condition (S=1), and Eq. (13), provided by [7], respectively.

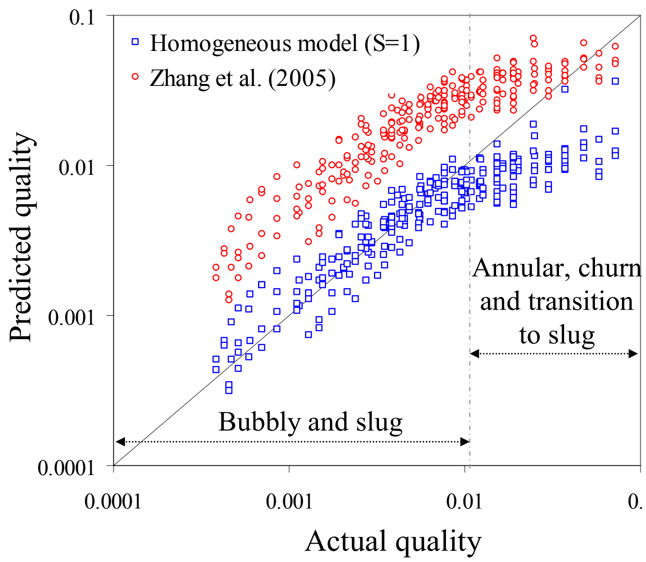

Fig. 9 - Comparison between experimental and predicted quality values using Eq. (3), assuming S =1, and Eq. (13), respectively

The quality predicted by Eq. (3) assuming the non-slip condition (S=1) was underestimated for most values. The performance was good for bubbly and slug regimes, but when the transition to churn and annular occurred, and mean void fractions over 0.7 and quality over 1% were reached, the predicted quality values deviated from the reference line. The fractional RMS deviation values were 43.8%.

The results obtained using the correlation in [7] overestimated the experimental values. In Eq. (13), c' = 0.5 and H = 0.65 were used for all experimental points. The correlation, created with an oil-air flow data set, did not obtain satisfactory results, and fractional RMS deviation values over 200% were reached.

For predicting the quality in air-water flow, a nonlinear regression was made with the entire experimental data set by means of a modified version of Eq. (13). Another constant was included in the void fraction term to better forecast the quality. Thus, it was possible to decrease the errors in the predictions due to the non-linearity caused by the different flow patterns. The multidimensional optimization was done using the variable metric algorithm, which uses numerical derivatives, from the Engineering Equation Solver (EES). The fractional RMS deviation values were 37.5 %. Equation (15) is presented below.

$$x = 0,5\left(\frac{\alpha}{1-\alpha}\right)^{1,3}\left(\frac{\rho_g}{\rho_l}\right)^{0,9} \tag{15}$$

4.4 Two-phase Mass Flow Rate

This section reports the predictions for the two-phase mass flow rate obtained by means of the homogeneous model and the correlations of Chisholm (1967), Zhang *et al.* (1992) and Zhang *et al.* (2005). According to the upward vertical and

Table 4 - Values of the fractional RMS deviation (%) for the two-phase mass flow rate

m_{TP}, predicted by:	Orifice Plate			Venturi		
	Horizontal	Vertical	**Total**	Horizontal	Vertical	**Total**
Homogeneous Model	22.6	22.2	22.4	7.8	9.3	8.6
Chisholm (1967)	11.9	11.0	11.5	8.9	6.8	7.9
Zhang *et al*. (1992)	9.4	9.3	9.4	28.9	26.0	27.6
Zhang *et al*. (2005)	10.4	5.5	8.4	12.3	11.9	12.1
Zhang *et al*. (2005)*	8.3	4.2	6.6	6.1	3.1	4.8

* With the constants obtained in the present study, see Table 5.

horizontal maps previously shown, the experimental points to be predicted are represented by squares.

Through the experimental quality obtained by the rotameters and the densities of the fluids, it is possible to calculate the K_L parameter of Equations (4) and (11). To obtain the K_L value of Eq. (10) it is still necessary to use the experimental slip ratio obtained by means of Eq. (3).

On the other hand, to obtain the K_L value of Eq. (12), the densities of the fluids, the experimental void fraction and the values of the constants are required. In Eq. (12), values of c = 0.50, n = *0.95* and m = 0.02 were used for all experimental points.

After calculating all K_L terms, it is possible to predict the two-phase mass flow rate through Eq. (2), by means of the discharge coefficient defined previously and the differential pressure measured in the meters, venturi and orifice plate. Figures 10, 11, 12 and 13 show graphically the results obtained using the homogeneous model, and the correlations of Chisholm [10], Zhang *et al*. [5] and Zhang *et al*. [7], respectively.

Table 4 summarizes the results obtained for each correlation, showing the values of the fractional RMS deviations (%) for the experimental two-phase mass flow rate. The correlations for each meter are given for each direction (horizontal and vertical) and for both directions (total).

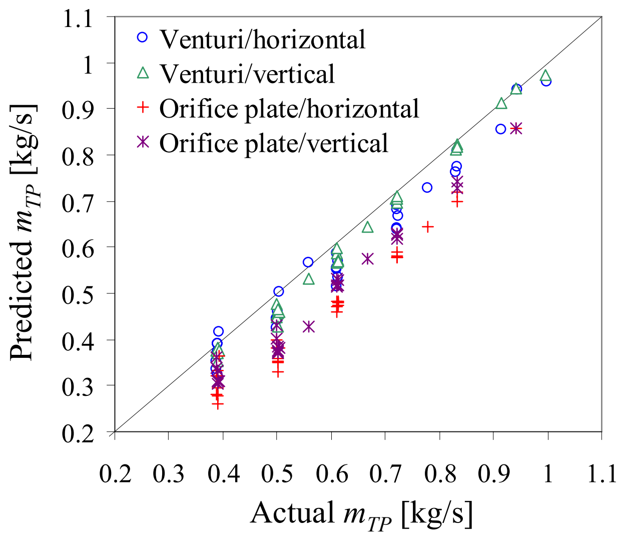

Fig. 10 - Comparison between experimental two-phase mass flow rate and that predicted by the homogeneous model

Lower values for the fractional RMS deviation were encountered for the venturi in Fig. 10. A deviation of 8.6% was obtained for this meter, including both tested directions. Reasonable accuracy and precision were obtained. The circles and triangles are close to the reference line.

Higher values for the RMS deviation were obtained for the orifice plate. The experimental points presented good accuracy, but not precision. The presence of this meter causes important disturbance in the two-phase flow and its use in the homogeneous model appears inappropriate.

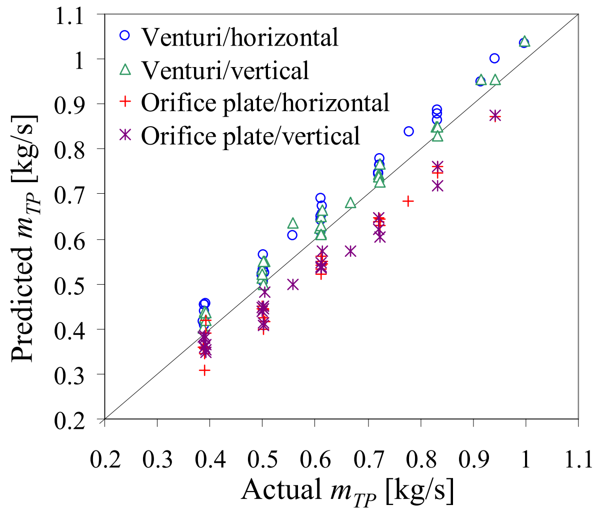

Fig. 11 - Comparison between experimental two-phase mass flow rate and that predicted according to Chisholm (1967)

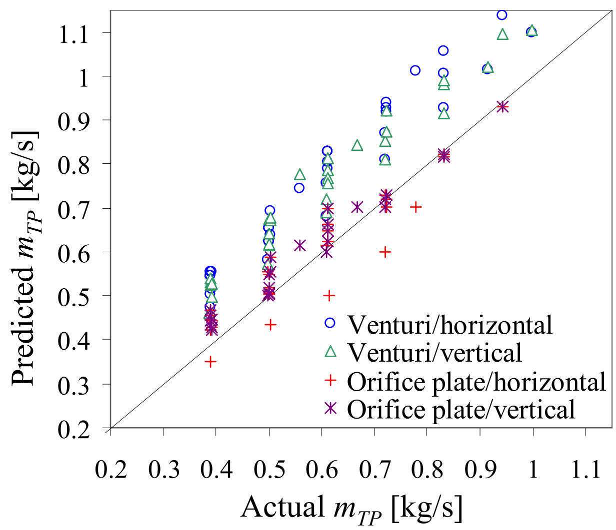

Fig. 12 - Comparison between experimental two-phase mass flow rate and that predicted according to Zhang *et al*. (1992)

As with the homogeneous model, Chisholm's correlation achieved better results with the venturi. A deviation of 6.8% was obtained for this meter in the vertical direction. Higher deviations were observed for the orifice plate. It should be noted that Chisholm's correlation had the best performance of all the tested correlations.

The correlation of Zhang *et al.* (1992) overestimated the two-phase mass flow rate when used for the venturi meter. Also, high deviation values were obtained. For the orifice plate, however, deviations close to 9% were observed. This better result is to be expected, since the correlation was created using experimental data obtained with an orifice plate.

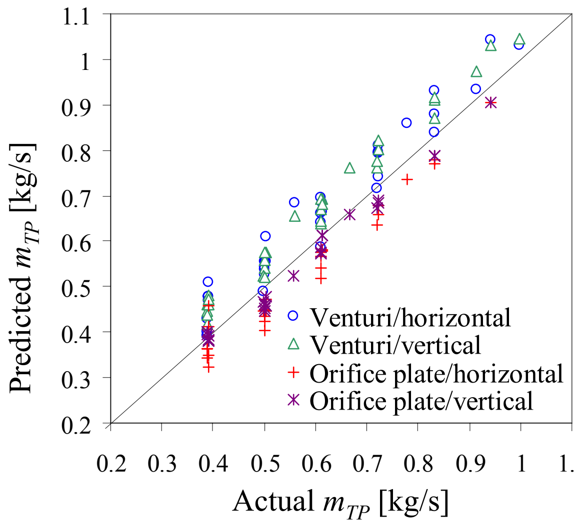

Fig. 13 - Comparison between experimental two-phase mass flow rate and that predicted according to Zhang *et al.* (2005)

The correlation of Zhang *et al.* (2005) had a reasonable performance in predicting the two-phase mass flow rate. However, better results were found for the orifice plate. This was not expected, since this correlation was created with experimental data obtained through measurements with a venturi in an oil-air two-phase flow. A deviation of 5.5% was obtained for the orifice plate in the vertical direction.

To obtain new values for the constants of this correlation, a nonlinear regression was applied with the actual data set. The same multidimensional optimization utilized in the section 4.3 was used. These new values are presented in Table 5.

Table 5 - Constants for [7] by means of the actual data set

	c	*n*	*m*
Orifice Plate	0.40	1.14	2.36
Venturi	0.50	1.01	0.09

5. CONCLUSIONS

A comparative study between the performance of a venturi and an orifice plate in a low quality (x<0.011) air-water flow was carried out. Also, a system consisting of one of the flow meters, thermocouples, absolute and differential pressure transducers, and a resistive void fraction sensor was tested for measurement of the air-water mass flow rates without separating the fluids.

An insignificant influence of gravity in the pressure drop for both meters was noted. For each meter, the mean ratio between the pressure drops with horizontal and vertical flow was close to 1. The mean ratio between the pressure drops in the orifice plate and in the venturi was 1.81.

A mean slip ratio of 1.06 was obtained for bubbly and slug patterns for the experimental pressure levels, and the use of a non-slip condition (S=1), for α<0.7, was thus appropriate.

The homogeneous model and the correlation of Chisholm (1967) achieved good performance in predicting the two-phase mass flow rate for the venturi meter, and the correlation of Zhang *et al.* (2005) for the orifice plate. In some cases, deviations between 5 and 10 % were achieved.

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NOMENCLATURE

Latin Symbols

A	Venturi throat or orifice area	m^2
c	Zhang's constant	Dimensionless
c'	Zhang's constant	Dimensionless
C	Chisholm's correction factor	Dimensionless
C_d	Discharge coefficient	Dimensionless
D	Diameter	m
F_a	Thermal expansion correction factor	Dimensionless
g	Gravity acceleration	m/s^2
G	Mass flux	kg/m^2s
H	Zhang's constant	Dimensionless
j	Superficial velocity	m/s
K_L	Two-phase correction factor	Dimensionless
m	Mass flow rate	kg/s
m	Zhang's constant	Dimensionless
N	Total number of samples	Dimensionless
n	Zhang's constant	Dimensionless
Re	Reynolds number	Dimensionless
S	Slip ratio	Dimensionless
v	Mean velocity	m/s
x	Quality	Dimensionless
X	Lockhart-Martinelli parameter	Dimensionless
Y	Compressibility coefficient	Dimensionless

Greek Symbols

α	Mean void fraction	Dimensionless
β	Throat (or orifice) diameter to pipe diameter ratio	Dimensionless
ρ	Density	kg/m^3
λ	Baker's parameter	Dimensionless
ψ	Baker's parameter	Dimensionless
Δp	Pressure drop	Pa

Subscripts

D	Diameter
g	Gas
l	Liquid
OP	Orifice plate
TP	Two-phase
V	Venturi

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