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# A new Spool Piece for horizontal two-phase flow measurement

**G Monni, M De Salve and B Panella**

Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy

E-mail: [grazia.monni@polito.it](mailto:grazia.monni@polito.it)

**Abstract.** This work presents the characterization of a Spool Piece (SP), made up of a Classical Venturi and a Wire Mesh Sensor (WMS), that are installed in a horizontal test section, in which an air-water mixture flows. The test section consists of a horizontal Plexiglas pipe of internal diameter 19.5 mm and total length of about 7 m. The flow quality ranges from 0 to 0.73 and the superficial velocity ranges from 0.14 to 32 m/s for air and from 0.019 to 2.62 m/s for water; the pressure ranges from atmospheric pressure to 4 bar depending on the experimental conditions. The observed flow patterns are stratified-bubbly-slug/plug-annular. The instrument response is analyzed and discussed. From the signal analysis the mass flow rate of each phase is obtained. The developed model allows the evaluation of the mass flow rate with an accuracy higher than 20% in the 84% of the cases and with an accuracy higher than 10% in the 73.3% of the cases. Finally the introduction of the estimated parameters in the SP model is considered and discussed.

## 1. Introduction

Within the framework of an Italian R&D program on Nuclear Fission, managed by ENEA and supported by the Ministry of Economic Development, the SPES3 experimental facility [1], able to simulate the innovative small and medium size PWR nuclear reactors, is being built and will be operated at SIET Company laboratories. In such facility some design and beyond design basis accidents, like LOCAs, with and without the emergency heat removal systems, will be simulated. An accurate accident analysis requires the measurement of the mixture mass flow rate and therefore instruments and methodologies to evaluate different two-phase flow parameters need to be developed.

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. Each instrument of the SP has to be sensitive to the different properties of the flow, like momentum, velocity, density, void fraction; moreover the selection of the instruments strongly depends on the experimental conditions: pressure, temperature and phases velocities. A different number of instruments can be coupled in a SP; a low number of instruments allows the reduction of costs, complexity and space requirements, but on the other hand, it requires the introduction of theoretical or experimental models able to compensate for the lacking of information. As the response of a meter in a two-phase flow tends to be highly sensitive to the flow pattern, to the upstream configuration and flow history, one of such instruments has to be able to measure the void fraction. Wire Mesh Sensors (WMS), based on the measurement of the local instantaneous conductivity of the two-phase mixture, are used for the evaluation of local void fraction, bubble size distributions and gas velocity distributions. The WMS



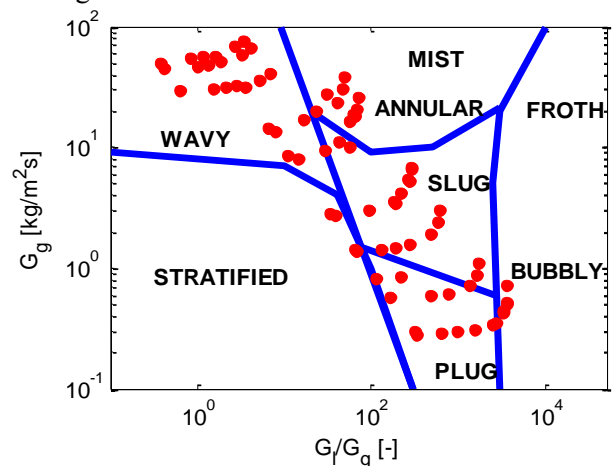
has been used, in different geometry and for different configurations, to study mean cross-section void fraction and gas profile evolution [2]. In this paper a SP made up of a Venturi Flow Meter (VFM) with a Wire Mesh Sensor (WMS) is proposed. The calculation of fluid flow rate by reading the pressure drop across a pipe restriction is perhaps the most commonly used flow measurement technique in industrial applications. Compared with single-phase flow, the pressure drops in two-phase flow increase due to the interaction between the gas and the liquid phase; for this reason the value of the effective two-phase mass flow rate is over-predicted and must to be corrected using available correlations derived from experimental data or semi-empirical models.

In the present paper, the results of the experimental work carried out to analyze the response of a SP made up of a VFM and a WMS are shown. The SP has been tested in a horizontal test section for air-water flows in a large range of phases mass flow rates. The methodology for the signals interpretation, the developed model of the SP for the phases mass flow rates estimation and the results are presented and discussed.

## 2. Experimental Facility and Test Matrix

The experimental facility consists of the feed water loop (tap water with conductivity of about 620  $\mu\text{S}$  is used), the feed air loop and the test section. The liquid flow rate is measured by means of an electromagnetic flow meter in a range of 0.9-36  $\text{m}^3/\text{h}$  with a  $\pm 0.5\%$  r.v. accuracy value. Lower values of the water flow rate are measured by means of rotameters in the ranges of 0-100 l/h and 100-400 l/h with an accuracy value of  $\pm 2\%$  r.v.. The air flow rate is measured by means of different rotameters for the different ranges (100-500  $\text{NI}/\text{h}$ , 1000-5000  $\text{NI}/\text{h}$  and 6300-63000  $\text{NI}/\text{h}$ ) with a  $\pm 2\%$  f.s.v. accuracy value. The test section [3] consists of a 19.5 mm diameter and 7 m long pipe. The SP is installed at  $L/D = 192$  from the entrance; the WMS is installed between two Plexiglas pipes having a length of 600 mm, while the VFM is installed between two Plexiglas pipes having a length of 500 mm and 490 mm upstream and downstream respectively. The inlet pressure ranges from atmospheric pressure to 4 bar depending on the experimental conditions. The flow is discharged at atmospheric pressure. The experimental test section is equipped with two quick closing valves (QCV) that allow the measurement of the volumetric void fraction in a length of 1300 mm.

The pressure drop in the VFM is measured by means of two differential pressure transducers having two different working range:  $-40 \div 40$  mbar and  $0 \div 1250$  mbar. The instruments signals are acquired in a LabView® environment by the National Instruments DAQ (Digital Acquisition) system (NI USB-6218). The WMS signals are instead acquired by means of the sensor software, synchronizing the measures through a trigger. The signals have been acquired using a frequency  $f = 1250$  Hz for all the instruments for a total acquisition time of 20 s. Instruments characterization in single-phase flow of air and water has been performed. Two-phase experiments have been carried out at water temperature of about 20 °C. The flow quality ranges from 0 to 0.73 and the superficial velocity from 0.14 to 32 m/s for air and from 0.019 to 2.62 m/s for water. The typical observed flow patterns were stratified flow, intermittent flow (slug and plug) and annular flow. The population of samples ranges over different flow patterns and it is more representative of intermittent flow regime and annular wavy flow regime. From visual observation and maps results (figure 1) it also clear that some runs have been performed in transition regimes.



**Figure 1.** Baker's Map [6] prediction of Flow Patterns

### 3. Spool Piece

#### 3.1 Wire Mesh Sensor Geometry and Signal Processing

The basic working principle of the sensor is the measurement of the conductivity of the fluid. Because air and water have different electrical properties (tap water is high conductive while air is very low conductive) the measurement of the conductance can be analyzed to detect the presence of each phase inside the pipe.

The sensor used in the present work has been constructed by Teletronic Rossendorf GmbH. The WMS consists of two planes of parallel wire grids (16x16) that are placed across the channel at a short distance from each other (1.5 mm) and span over the measuring cross section. The wires of both planes cross under an angle of 90°. The sensor has been designed to cover the cross section of a pipe having an internal diameter equal to 19.5 mm: the wires have a diameter  $D_{wire}$  of 70  $\mu\text{m}$  and a pitch  $p$  equal to 1.3 mm, so that only the 5.4% of the pipe section is occupied by the sensor. The measuring grid allows to obtain a spatial resolution of the order of the pitch length (1.3 mm) and a very high time resolution. The WMS sensor signals are acquired by means of WMS200 electronics and processed in Matlab® environment. The output is a 3-D matrix  $V(i,j,k)$  proportional to the local fluid conductivity. The indexes  $i$  and  $j$  refer to transmitting wires and to receiving wires respectively, while  $k$  is the time index. First of all the signal is normalized taken into account the single-phase reference matrix. The signal normalization can be considered as an approximation of the local void fraction value, if a linear relationship between conductivity and void fraction and a reference area equal to the square of the wire pitch  $p$  are assumed.

$$V^*(i, j, k) = \frac{V(i, j, k) - V_l(i, j)}{V_g(i, j) - V_l(i, j)} \quad (1)$$

where  $V_l$  and  $V_g$  are the time averaged values of the signals with the pipe filled with water or air at the beginning of the test. From the normalized signal the mean cross-section instantaneous void fraction is derived taking into account the location of the wires respect to the pipe. The points of the grid, that are located near the wall, are analyzed taken into account the wall influence, while the points, that are located outside the cross section of the pipe are excluded from the analysis; so the local instantaneous void fraction is calculated as:

$$\alpha(i, j, k) = \frac{V^*(i, j, k) - 1}{a(i, j)} + 1 \quad (2)$$

where  $a(i,j)$  is the geometrical weight factor.

The local instantaneous void fraction  $\alpha$  has been obtained with an acquisition frequency  $f_{acq}$  equal to 1250 Hz for a total observation time  $T_T$  equal to 20 s, so that the value of  $k$  ranges from 1 to  $k_T$ , where  $k_T$  is the total number of measured frames, that can be expressed by the eq.

$$k_T = f_{acq} \cdot T_T \quad (3)$$

The averaged time cross-sectional void fraction is obtained by averaging over the observation time and over the measuring section:

$$\langle \alpha \rangle = \frac{1}{k_T} \sum_{k=1}^{k_T} \frac{1}{A} \sum_{i=1}^{16} \sum_{j=1}^{16} \alpha(i, j, k) \quad (4)$$

where  $A$  is the pipe cross section.

### 3.2 WMS Measurement Accuracy

Errors of the wire-mesh sensor measurements for the gas fraction are mainly caused by the pitch of the wires which is 1.3 x 1.3 mm and the distance of the wire planes that is 1.5 mm.

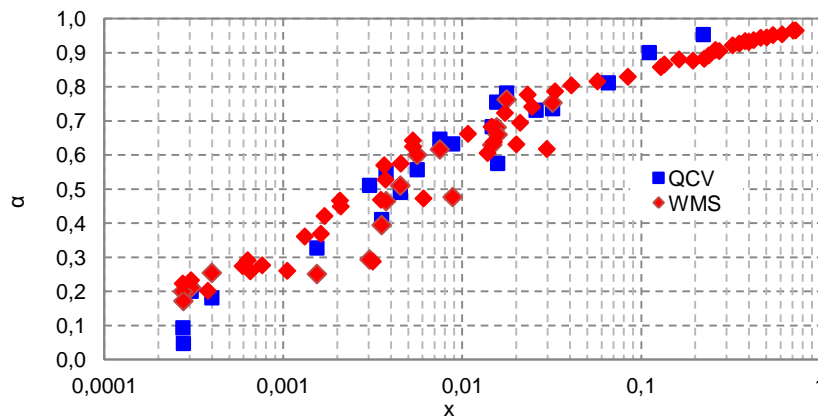
Comparative measurements between the wire-mesh sensor and other research methods supplied information on the accuracy of the measurement technique and the evaluation algorithms for the experimental determination of these flow parameters. An air/water flow with gas volume fraction ranging from 0 to 100% shows that the deviations between wire-mesh sensor and gamma measurements are limited to  $\pm 5\%$  [2]. Comparative measurements between wire-mesh sensor and an X-ray tomography were also performed for air/water flow [4]. It was found that, the accuracy of the gas volume fraction averaged over the flow cross-section depends on the two-phase flow regime.

Differences in the absolute void fraction were determined for bubbly flows in the range of  $\pm 1\%$ , while a systematic underestimation of  $- 4\%$  was observed for slug flows. In the present work, the experimental void fraction is compared with the volumetric void fraction measured with the quick closing valves method. The volumetric void fraction

$$\langle \alpha_v \rangle = \frac{1}{V} \int_V \alpha(x, y, z) dV \quad (5)$$

is measured in the 1300 mm long first part of the test section, with a precision of 3%.

Due to the intermittence of the flow, the volumetric void fraction is measured more than one time for each tested flow rates combinations in order to derive a representative mean value. In figure 2 the void fraction measured using the QCV technique and by means of the WMS are shown as a function of the flow quality. Compared to the volumetric void fraction, the void fraction measured with the WMS shows a higher dispersion in the range of intermittent flows and it's in good agreement at very high void fraction when the flow becomes annular. Moreover the WMS gives lower values of void fraction for the flow characterized by flow qualities higher than 0.01 and gives higher values at flow qualities lower than 0.001. Because the volumetric void is measured at the entrance of the test section, the flow is not completely developed, and an L/D effect can be present. A series of measurement in the volume where the WMS is installed will give more accurate information.



**Figure 2.** Mean void fraction measured using the QCV method and the WMS

### 3.3 Venturi Flow Meter

The characteristics of the Venturi flow meter are shown in table 1. Because in the experimented range the Re number is lower than  $10^5$  and because the sensor geometrical dimensions are not inside the range considered in the EN ISO 5167-1 [5], an in-situ calibration has been performed to obtain the single-phase discharge coefficient for air and water:

$$C_{l,g} = \left[ \frac{W}{F_a \cdot Y \cdot A_2} \cdot \left( \frac{(1 - \beta^4)}{2\rho \cdot \Delta p} \right)^{0.5} \right]_{l,g} \quad (6)$$

The experimental discharge coefficient has been found equal to 0.94 in water flow and 0.97 in air flow, at Reynolds numbers higher than 15000.

**Table 1.** VFM Data

Type Herschel (Fluid: Water)		
$D_1$	26	mm
$D_2$	10.251	mm
$\beta$	0.394	-
$\Delta p$	68.6 (700)	mbar (mmH <sub>2</sub> O)
$W_{\text{water}}$	300	g/s
$L_{\text{upstream}}$	500	mm
$L_{\text{downstream}}$	490	mm

Compared to the single-phase flow measurements, in two-phase flow, the VFM pressure drops are higher due to phases interaction, and a model for the signal interpretation must to be used.

Baker [6] describes the different approaches used by the different researchers: estimation of the phases mass flow rates based on the estimation and/or calculation of the two-phase flow density and two-phase flow discharge coefficient and estimation of the phases mass flow rates based on the two-phase flow multipliers, relating single-phase and two-phase flow pressures drops. In 1949, Lockhart and Martinelli [7] researched the pressure drop and the liquid holdup of two-phase flow across the pipe, which became an important basis for the differential pressure method in two-phase flow measurement research. Later, many researchers studied the relationship between the mass flow rate of gas-liquid flow and the differential pressure across the flow meter. Flow rate measurement correlations were reported in [8] and [9], and recently in [10] and [11]. The developed correlations have been derived in a very limited operating range (pressure, temperature, phases velocities, fluids, etc..) and are strongly dependent on the VFM geometry ( $\beta$ ,  $D_1$ ,  $D_2$ ,  $L$ , etc..). Moreover the most part of the available correlations are valid for very high ( $x > 0.95$ ) or very low ( $x < 0.1$ ) flow quality values.

The general equation of the VFM in a two-phase flow can be written as:

$$W = K \cdot \sqrt{2\Delta p_{TP} \rho_{TP}} \quad (7)$$

where

$$K = \frac{C_{TP} \cdot F_a \cdot Y}{\sqrt{1 - \beta^4}} A_2 \quad (8)$$

Considering the value of  $Y$  and  $F_a$  equal to one, the two parameters, that have to be defined, are the two-phase discharge coefficient and the two-phase density.

In two-phase flow, due to the presence of the slip between the phases, different types of density can be defined, depending on the flow model hypothesis (Homogeneous, Separated flow, etc..). In the present work the density defined on the momentum balance is used to analyze the VFM response:

$$\rho_{TP} = \left[ \frac{x^2}{\alpha \rho_g} + \frac{(1-x)^2}{(1-\alpha) \rho_l} \right]^{-1} \quad (9)$$

In order to estimate the density, the void fraction value must be known; then the output of the WMS becomes an input for the VFM signal interpretation. The two-phase flow discharge coefficient is then evaluated, based on the experimental data (figure 3 (a)). The dependence of the parameter  $C_{TP}$  on the two-phase Re number has been modeled as (figure 3 (b)):

$$\begin{cases} C_{TP} = a + b \cdot \sqrt{\frac{10^c}{\text{Re}_{TP}^d}} & \text{Re}_{TP} < 1.5 \cdot 10^4 \\ C_{TP} = 0.91 & \text{Re}_{TP} > 1.5 \cdot 10^4 \end{cases} \quad (10)$$

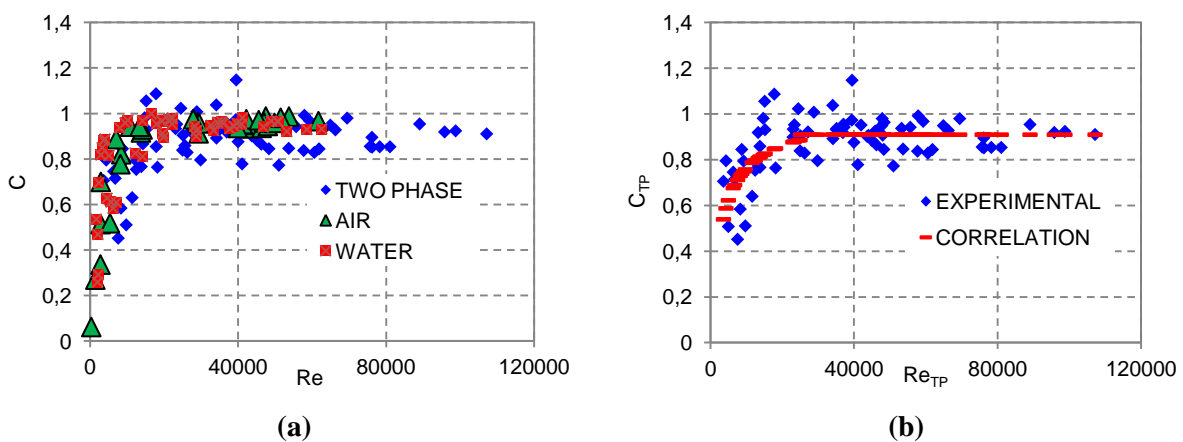
with the parameters evaluated on the basis of the experimental data:  $a=1.1$ ,  $b=0.6$ ,  $c=3.5$  e  $d=1$ .

The Reynolds number has been defined as:

$$\text{Re}_{TP} = \frac{G_{TP} D_{pipe}}{\mu_{TP}} \quad (11)$$

and the dynamic viscosity  $\mu$ , in accordance with the two-phase density (Eq. 9), has been defined as:

$$\mu_{TP} = \left[ \frac{x^2}{\alpha \mu_g} + \frac{(1-x)^2}{(1-\alpha) \mu_l} \right]^{-1} \quad (12)$$



**Figure 3.** VFM discharge coefficient. (a) experimental single and TP flow; (b) TP flow correlation

The experimental pressure drops of the VFM have been analyzed in order to highlight the dependence on the superficial velocities of the phases. The  $\Delta p$  value increase is shown in figure 4 as a function of the two-phases superficial velocities. The regular behavior of the increasing curves suggests that a model of the instrument, depending on the phases velocities, can be developed in order to avoid the use of the discharge coefficient correlations, for the mass flow estimation. The lack of data between  $J_g = 3$  m/s and  $J_g = 6$  m/s is due to the non complete superimpositions ranges of the air mass flow meters.

In figure 5, the pressure drops in the VFM are expressed in terms of two-phase flow multipliers. The multipliers  $\Phi_{1,g}^2$  has been evaluated as the ratio between the two-phase flow pressure drop and the single-phase pressure drop at the same phase mass flow rate:

$$\Phi_l^2 = \frac{\Delta p_{TP}}{\Delta p_l} \tag{13}$$

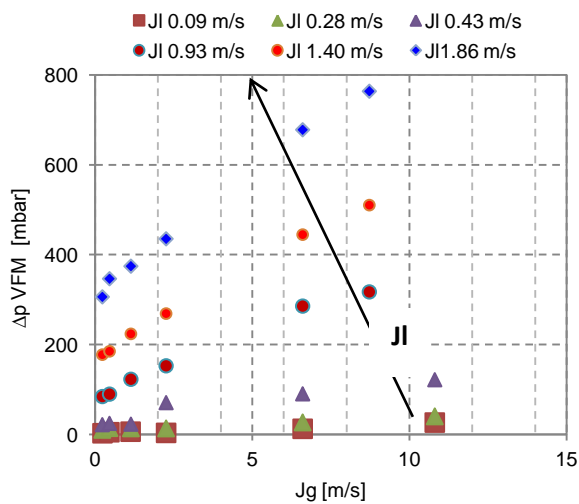
respect to the liquid single-phase flow, and

$$\Phi_g^2 = \frac{\Delta p_{TP}}{\Delta p_g} \tag{14}$$

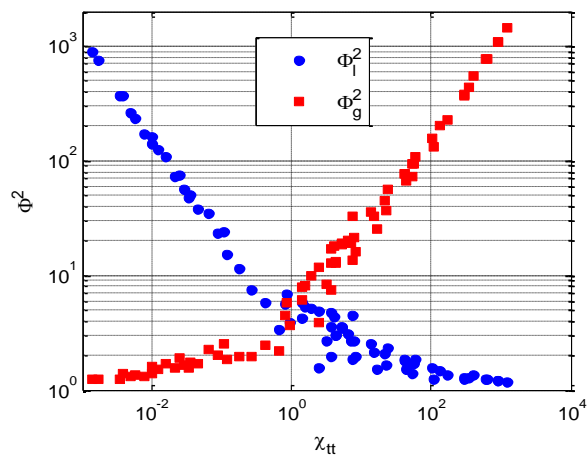
respect to the air single-phase flow.

In the x-axis is reported the experimental Lockart-Martinelli parameter, that is evaluated as the ratio between liquid and gas VFM pressure drops:

$$\chi_{tt} = \frac{\Delta p_l}{\Delta p_g} \tag{15}$$



**Figure 4.** Experimental VFM pressure drops as a function of phases superficial velocities



**Figure 5.** VFM pressure drops two-phase multipliers

### 3.4 Spool Piece Model

The SP model consists of a set of equations that, based on the measurement of the VFM pressure drop, and on the measurement of the void fraction in the WMS, together with the measurement of pressure and temperature of the fluid, allows the estimation of the mass flow rate of the phases in the test section:

$$\begin{cases} x = f_1(\alpha) \\ J_l = f_2(\alpha, \Delta p_{VFM}, p) \\ J_g = f_3(\alpha, \Delta p_{VFM}, p) \end{cases} \tag{16}$$

In the present work, an iterative approach is adopted for the estimation of the two mass flow rate of the phases. The model input are the void fraction, the pressure drop in the VFM, and the properties

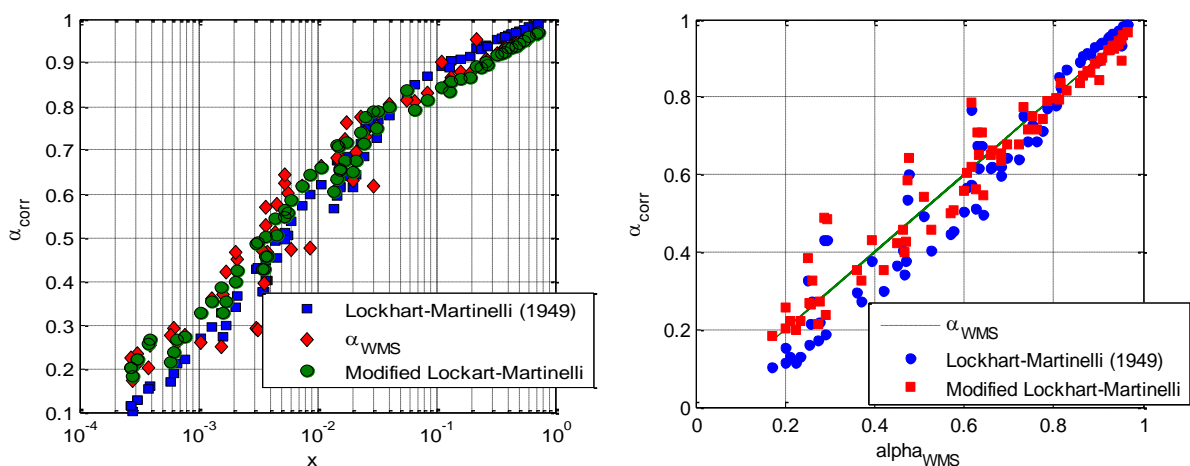


of air and water that are evaluated at the working pressure and temperature. An initial guess value for the flow quality is introduced. Using a literature  $x$ - $\alpha$  correlation the void fraction is calculated and the flow quality value is iterated till the error between the void fraction calculated and the void fraction measured by the WMS is lower than a threshold value ( $10^{-4}$ ). When the required accuracy is reached, the two-phase flow Reynolds number and the discharge coefficient are calculated in a new iterative loop, where for the first iteration  $C_{TP}=C_l$  is assumed. When the convergence is got ( $W_{TP,i}-W_{TP,i-1}<10^{-4}$ ) the mass flow rate are calculated for the two-phases. For the  $x$ - $\alpha$  correlation used in the calculation, the Lockhart-Martinelli correlation (17) has been modified, based on the experimental data:

$$\alpha = \left[ 1 + 0.28 \cdot \left( \frac{1-x}{x} \right)^{0.6} \cdot \left( \frac{\rho_g}{\rho_l} \right)^{0.36} \cdot \left( \frac{\mu_l}{\mu_g} \right)^{0.07} \right]^{-1} \quad (17)$$

$$\left\{ \begin{array}{l} \alpha = \left[ 1 + 0.2 \cdot \left( \frac{1-x}{x} \right)^{0.6} \cdot \left( \frac{\rho_g}{\rho_l} \right)^{0.36} \cdot \left( \frac{\mu_l}{\mu_g} \right)^{0.07} \right]^{-1} \quad x < 1 \cdot 10^{-3} \\ \alpha = \left[ 1 + 0.28 \cdot \left( \frac{1-x}{x} \right)^{0.6} \cdot \left( \frac{\rho_g}{\rho_l} \right)^{0.36} \cdot \left( \frac{\mu_l}{\mu_g} \right)^{0.07} \right]^{-1} \quad 10^{-3} \leq x \leq 6 \cdot 10^{-2} \\ \alpha = \left[ 1 + 0.45 \cdot \left( \frac{1-x}{x} \right)^{0.6} \cdot \left( \frac{\rho_g}{\rho_l} \right)^{0.36} \cdot \left( \frac{\mu_l}{\mu_g} \right)^{0.07} \right]^{-1} \quad x > 6 \cdot 10^{-2} \end{array} \right. \quad (18)$$

The comparison between the original correlation, the modified correlation and the void fraction value obtained from the WMS signal analysis is shown in figure 6.

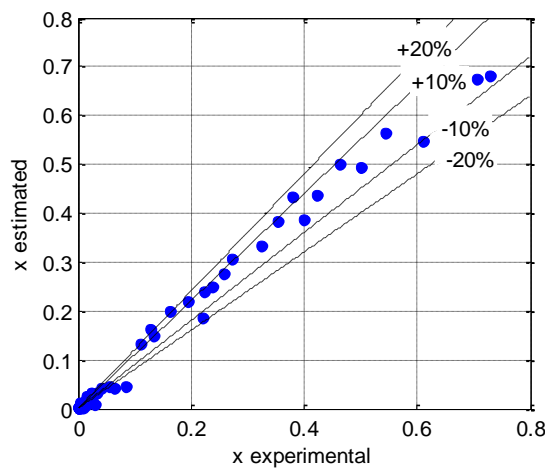


**Figure 6.** Comparison between WMS void fraction and correlations

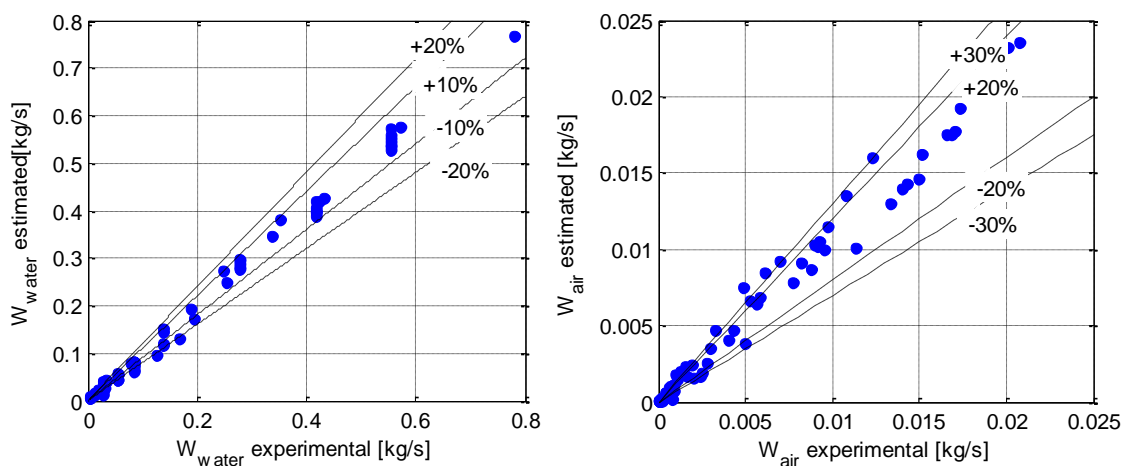
#### 4. Results

The developed SP Model has been applied to the experimental data in order to derive the mass flow rate of the phases. In figure 7, the flow quality, that is estimated by the SP model, is compared with the experimental value obtained by the phases flow rate measurements. The accuracy of the model has

been evaluated as the degree of closeness of the estimated quantity to the experimental value; and the estimation error is considered the distance between the estimated quantity and the experimental value. The flow quality is estimated with an error lower than 20% for the flows in which the quality was higher than 0.1, and the error is lower than 10% for the 72% of the runs. For flow qualities lower than 0.1 the estimation error increases and is lower than the 50% for the 90% of the cases. The estimated mass flow rates are shown in figure 8 (a) (water flow rate), and figure 8 (b) (air flow rate). The total mass flow rate is estimated with an error that in the 73.3% of the cases is lower than 10% and in the 84% of the cases is lower than 20%. The highest estimation errors concern the air flow rate; in fact it is more affected by the errors in the quality estimation and in the total mass flow rate estimation due to the small values of this parameter. In this case the error is lower than 30% for the 73.3% of the cases. The highest errors have been obtained for the flows characterized by an intermittent behavior (slug/plug flow patterns). Moreover the intermittent flow has been realized in a region where the VFM discharge coefficient is strongly dependent on the Re number; and an error on the estimation of  $C_{TP}$  produces obviously an additional error on the mass flow rate estimation.



**Figure 7.** Experimental flow quality vs. SP flow quality



**Figure 8.** Experimental mass flow rate vs. SP mass flow rate for water phase (a) and air phase (b)

## 5. Conclusions

The analysis of the signals and the developed model of the SP, made up of VFM and WMS, allow us to estimate the mass flow rate of the phases in air-water horizontal flows with a good accuracy in a large range of the flow quality. The mass flow rate has been estimated with an error lower than 10% in the 73.3% of the cases. Moreover the estimation error is considerably lower for the flow characterized by high values of quality and void fraction. In this range, with reference to facility SPES3 test conditions, the error in the mass flow rate estimation is always lower than 10% and 20% for water and air respectively.

## Nomenclature

A	area (m <sup>2</sup> )	<i>Special characters</i>	
C	VFM discharge coefficient	$\alpha$	void fraction
D	diameter (m)	$\beta$	D <sub>2</sub> /D <sub>1</sub> VFM diameter ratio
F <sub>a</sub>	VFM thermal expansion correction factor	$\mu$	dynamic viscosity (Pa·s)
G	mass flux (kg/m <sup>2</sup> s)	$\rho$	density (kg/m <sup>3</sup> )
J	superficial velocity (m/s)	$\sigma$	surface tension (N/m)
Re	Reynolds number	$\Delta p$	differential pressure (bar)
SP	Spool Piece	<i>Subscripts</i>	
V*	WMS normalized signal	g	gas
W	mass flow rate (kg/s)	i	i-th vertical wire index
Y	VFM compressibility coefficient	j	j-th horizontal wire index
f	signal acquisition frequency (Hz)	k	WMS time index
f.s.v	full scale value	l	liquid
p	pressure (bar)	TP	Two-Phase
r.v	read value	1	pipe area subscript
x	flow quality	2	VFM constricted area subscript

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