Multiphase Science and Technology, Vol. 21, No. 1–2, pp. 157–168, 2009

A NEW METHOD OF MEASURING TWO-PHASE MASS FLOW RATES IN A VENTURI

He Peixiang,[1] **Cees van der Geld,**[1] **Claudio Alimonti,**[2] **and Júlio César Passos**[3]

[1]*Faculty of Mechanical Engineering, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands*

hpx65@yahoo.com; C.W.M.v.d.Geld@tue.nl

[2]*A1University "La Sapienza" of Rome, Italy*

C.Alimonti@uniroma1.it

[3]*Departamento de Enga. Mecânica-LEPTEN/Boiling-Centro Tecnológico, Universidade Federal de Santa Catarina, Campus Universitário, 88.040-900 Florianópolis-SC, Brazil*

jpassos@emc.ufsc.br

Abstract. Metering of the individual flow rates of gas and liquid in a multicomponent flow is of great importance for the oil industry. A convenient, nonintrusive way of measuring these is the registration and analysis of pressure drops over parts of a venturi. Commercially available venturi-based measuring equipment is costly because it also measures the void fraction. This paper presents a method to deduce the individual mass flow rates of air and water from pressure drop ratios and fluctuations in pressure drops. Not one but two pressure drops are used and not only time-averaged values of pressure drops are utilized. As a proof-of-principle, prediction results for a horizontal and vertical venturi are compared with measurements for void fractions up to 80%. Residual errors are quantified and the effect of variation of equipment and of slip correlation is shown to be negligible. At relatively low cost a good predictive capacity of individual mass flow rates is obtained.

1. INTRODUCTION

This paper reports results of a joint research project, taking place in Italy, Brazil, and the Netherlands, about multiphase flow metering with a venturi. The goal is the design of a prediction method for the individual volume or mass flow rates of gas and liquid in a pipe system based *only* on pressure drop measurements along a venturi, without additional equipment such as void fraction meters. This extension of a well-known method for single-phase flow is not trivial for two-phase flow (Thorn *et al.*, 1997). Commercially available venturi-based multiphase mass flow meters are quite expensive because of their need to use a void fraction meter (see, for example, the website of Schlumberger). The present study aims at flow metering *without* a void fraction meter by extracting equivalent two-phase flow information from the measurement of time-averages and root–mean–square (rms) values of several pressure drops in a venturi. It is quite well known that pressure drop fluctuations in a straight tube indicate the flow pattern present (Tutu, 1982; van der Geld, 1985). The power in a relevant band of frequencies, typically 0–20 Hz, or the equivalent rms value, is related to the flow regime present. In addition, two-phase flow is redistributed in a venturi in such a way that the pressure drops upstream and downstream of the throat are different in a way that may depend on flow regime and void fraction. A typical example of this is given in Fig. 1, where differences upstream and downstream of the throat of a water–air mixture are clearly seen. This effect is further investigated and quantified in the aforementioned joint research project and guides the selection of pressure drops in the present study.

The approach followed consists of simultaneously measuring flow patterns, void fractions, and pressure drops at various locations in a venturi. At least two pressure drops are selected, and the low-order moments of the signals (mean and variance) are used in an analysis to determine the individual flow rates (see the schematic of Fig. 2).

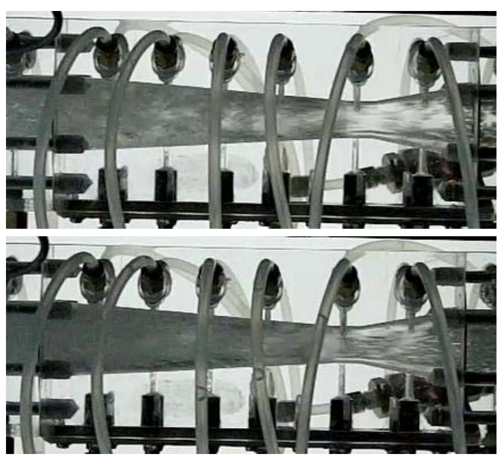

Figure 1 Typical examples of flow regime change in upward flow in the venturi. Flow is from right to left; throat diameter is 20 mm.

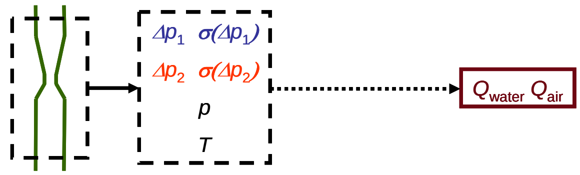

Figure 2 Schematic of measuring strategy which does not require void fraction measurement.

The present paper reports results for geometry and pressure drop choices depicted in Fig. 3. One pressure drop upstream and one downstream of the throat were selected.

Various such geometries are being studied: one with inlet diameter, D, of 21 mm is measured in Florianópolis (Brazil), the D = 40 mm venturi is measured in Eindhoven (The Netherlands), and in Rome a D = 50 mm bore tube was measured (Caudullo, 1996). Flow patters of the air–water system are visually observed. In the present study, measurements are reported that have been performed with a venturi with a circular cross section and with an inlet diameter, D, of 40 mm and a throat diameter, d, of 20 mm (see Fig. 3). Two orientations of the test section were investigated: vertical and horizontal. In this paper a proof of principle for predicting the two individual mass flow rates is given.

2. EXPERIMENTAL

The test rig is a closed loop for the water, with a pump and a mixing section upstream and an air–water separator downstream of the venturi depicted schematically in Fig. 3. Downstream pressure drops are designated with suffix b and upstream ones with suffix a. The main pressure drops to be used in the present study are those just across the convergent part, named ΔP_a, and that just across the divergent part, named ΔP_b. Tapping lines have been carefully deaerated.

Temperature is measured at one location upstream of the venturi and is used to compute the average gas mass density as a function of temperature and pressure in the following way. The mass density of air is 1.2041 kg/m^3 at pressure 101.325 kPa and temperature 21.1°C. The mass density of air is calculated at the gauge pressure P_{throat} (kPa) and at temperature t (°C) from

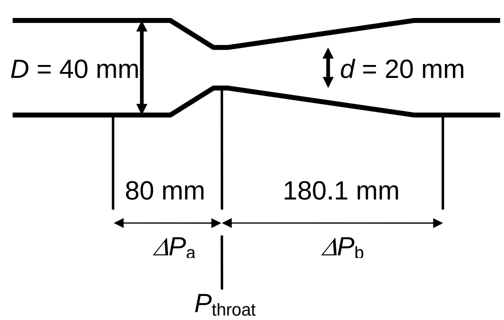

Figure 3 Schematic of venturi used.

$$\rho_{\text{air}} = 1.2041\{(273.15 + 21.1)/(273.15 + t)\}\{(101.325 + P_P)/101.325\} \tag{1}$$

The compressibility of the gas is accounted for in a way described below [see Eq. (3)]. Measurements reported in this paper were performed at room temperature and at ambient pressure.

List of instruments, ranges, and accuracies:

- Differential pressure drop sensors:
  1. Druck, PMP 4170, 0–1 bar , ±0.04% of full scale.
  2. Druck, PMP 4170, 0–2 bar, ±0.04% of full scale.
  3. Druck, LPX 9381, 0–100 mbar, ±0.1% of full scale.
  4. Druck, LPX 9381, 0–200 mbar, ±0.1% of full scale.
- Pressure (gauge) sensor: Trafag, 0–2.5 bar, 0.5% of full scale, 4–20 mA.
- Gas mass flow meter: Side trak, 0–300 slpm, ±1.5% of full scale.
- Water flow meter: Burkert, 0.3–10 m/s, ±0.5% of full scale.
- Data loger: National Instruments, USB-6210, 250 kHz.

The measurements reported in this paper were performed with inlet diameter D = 40 mm and with throat diameter d = 20 mm (see Fig. 3).

3. RESULTS AND ANALYSIS

3.1 *Analysis of total volume flow rate and pressure drop over the convergent part*

Let $\beta = d/D$, with D the inner diameter of the pipe at the inlet and d the diameter of the venturi throat. The total volume flow rate, in m^3/s, is computed with the aid of the following expression:

$$Q = Q_{\text{water}} + Q_{\text{air}} = \xi c \varepsilon (\pi d^2/4)\{1 - \beta^4\}^{-0.25}\sqrt{(2\Delta P_a/\rho)} \tag{2}$$

Here ξ is a parameter used to account for two-phase flow effects in a way described further below [Eq. (7)], and other symbols will now be defined. The pressure drop ΔP_a is the frictional pressure drop over the converging part of the venturi, zero if flow is zero. Coefficient c is the coefficient of flow rate in the venturi, taken to be 0.995 (Shen and Wang, 2000). The coefficient ε is the expansion coefficient of the two-phase flow. For single-phase air flow the following well-known expansion coefficient exists:

$$\varepsilon_{\text{air}} = \sqrt{[k\tau^{2/k}(k-1)^{-1}\{1-\beta^4\}\{1-\tau^{2/k}\beta^4\}^{-1}(1-\tau^{1-1/k})(1-\tau)^{-1}]} \tag{3}$$

Here $\tau = P_{\text{throat}}/(P_{\text{throat}} - \Delta P_a)$ is the ratio of throat pressure to entry pressure in the venturi, and k is the ratio of specific heats, $k = c_p/c_v$. Based on this coefficient ε_{air}, the following two-phase flow expansion correction is used:

$$\varepsilon = \beta_a \varepsilon_{\mathrm{air}} + (1 - \beta_a) \tag{4}$$

where β_a denotes the homogeneous void fraction at the inlet, to be determined in a way described below (Section 3.2). Any discrepancy between actual expansion and the one predicted with Eq. (4) is accounted for by the correction coefficient ξ. Falcone *et al*. (2003) found that the single-phase flow expansion coefficient correction, i.e., $\varepsilon_{\mathrm{air}}$, if applied directly to the gas flow rate only, yields good agreement between measurements and predictions. We examined this possibility but obtained fitting characteristics that were a little worse than those presented below.

The mass density ρ in Eq. (2) is the two-phase flow mass density, which depends on the void fraction. The relation

$$\begin{aligned} \rho &= \{\rho_{\mathrm{air}} Q_{\mathrm{air}} + \rho_{\mathrm{water}} Q_{\mathrm{water}} s\}/(Q_{air} + Q_{\mathrm{water}} s) \\ &= \{\rho_{air} \beta_\alpha + (1 - \beta_\alpha)\rho_{\mathrm{water}} s\}/\{\beta_\alpha + (1 - \beta_\alpha) s\} \end{aligned} \tag{5}$$

shows that correlations for the slip, $s = u_{\mathrm{air}}/u_{\mathrm{water}} = (Q_{\mathrm{air}}/Q_{\mathrm{water}})(1 - \varepsilon)/\varepsilon = \psi(1 - \varepsilon)/\varepsilon$, yield estimates for the void fraction once the homogeneous void fraction, β_α, is known. The homogeneous void fraction is known exactly in laboratory experiments but otherwise has to be inferred from pressure drop measurements in a way described below (see Section 3.2). Five well-established correlations for the slip in homogeneous flow in straight tubes have been examined to predict the mass density from Eq. (5). Details about these correlations are given by Schmidt *et al.* (2008). It will be investigated, in Section 3.2, how the choice of slip correlation affects mass flow rate predictions.

The total calculation procedure is summarized in Fig. 4.

3.2 *Homogeneous void fraction and correction parameter ξ, horizontal flow*

The analysis of Section 3.1 shows that two parameters are needed in order to compute the total volume flow rate from Eq. (2): the homogeneous void fraction, β_α, and the correction parameter, ξ, which depends on the slip correlation selected to evaluate the mass density, ρ, with Eq. (5). This section deals with the assessment of these two parameters.

A convenient way to derive the homogeneous void fraction from measured pressure drops and from measured fluctuations in pressure drop is for horizontal venturis found to be given by the following polynomial expansion:

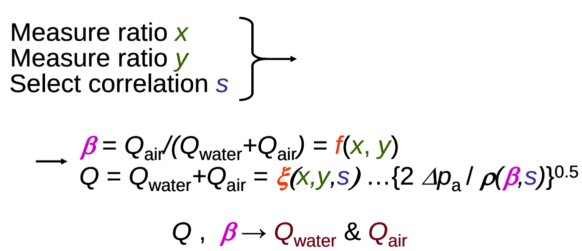

Figure 4 Schematic of calculation procedure of measuring strategy; functions f and ξ have to be determined.

$$\beta_\alpha = Q_{\rm air}/Q_{\rm air} + Q_{\rm water}) = a_{00} + a_{01}x + a_{02}y + a_{03}x^2 + a_{04}y^2 + a_{05}x^3 \qquad (6)$$

where the main parameters related to pressure drops are x and y, defined in the following way:

$$x = \sigma_{\Delta Pa}/\Delta P_a,\ y = \Delta P_b/\Delta P_a,\ \sigma_{\Delta Pa} = \sqrt{\left[(1/n)\sum_{i=1\ldots n}(\Delta P_{a,i} - \Delta P_a)^2\right]}$$

$$\Delta P_a = (1/n)\sum_{i=1\ldots n}\Delta P_{a,i},\ \Delta P_b = (1/n)\sum_{i=1\ldots n}\Delta P_{b,i}$$

$$\sigma_{\Delta Pb} = \sqrt{\left[(1/n)\sum_{i=1\ldots n}(\Delta P_{b,i} - \Delta P_b)^2\right]}$$

The rms values of pressure drop fluctuations are used because they are indicative of the flow regime present (see the Introduction section of this paper). The ratio of pressure drops measured, y, is found to be dependent on the individual mass flow rates of water and air, which constitutes one of the main findings of this study. The coefficients a_{0j} have been fitted to experimental data (see Table 1). The correlation coefficient, r^2, is high and also the F-statistic is high. Errors indicated are the 78 % errors.

The main parameters measured, x and y, should be independent of the sensor used. This has been validated by replacing one sensor with another one. The differences in x and y values were less than 5%, although the readings were quite different and the measurements were performed at different times.

A similar procedure was followed for the compensation coefficient ξ:

$$\xi = a_0 + a_1x + a_2y + a_3x^2 + a_4y^2 + a_5x^3 + a_6y^3 \qquad (7)$$

The fitting results of the coefficients are for the Zivi correlation given in Table 2. In this case only three coefficients suffice to predict the correction coefficient. More coefficients are needed for other slip correlations. For two other correlations, the one of Chisholm and the one of Schmidt *et al.*, the following equation has been employed, with x_1 given by $x_1 = \sigma_{\Delta Pb}/\Delta P_a$:

$$\xi = a_0 + a_1x + a_2x_1 + a_3x^2 + a_4x_1^2 + a_5x^3 + a_6x_1^3 \qquad (8)$$

The combination of Q and the homogeneous void fraction β_α yields both individual volume flow rates $Q_{\rm air}$ and $Q_{\rm water}$, (see also Fig. 4). Figures 5 and 6 compare predictions and measurements for both volume flow rates and for the Zivi correlation used for Table 2. The agreement is good. Discrepancies occur mainly for higher flow rates, which is probably a consequence of the strong fluctuations in the actual pressure drops that occur at these flow rates.

The errors for all five correlations investigated are compared in Table 3. The absolute error is defined by

Table 1 Coefficients in Eq. (6) to predict the homogeneous void fraction, β, for horizontal flows

a_{00} = 0.44 ± 0.01	a_{01} = 0.25 ± 0.03	a_{02} = –0.77 ± 0.03
a_{03} = –0.037 ± 0.01	a_{04} = –0.46 ± 0.12	a_{05} = 0.897 ± 0.13
r^2 = 0.985	F = 1745	

Table 2 Coefficients in Eq. (7) to predict the correction coefficient ξ in combination with the Zivi correlation for the slip; horizontal flows

a_0 = 1.50 ± 0.03	a_1 = 0.33 ± 0.07	a_2 = –2.26 ± 0.13
a_3 = 0	a_4 = 2.86 ± 0.5	a_5 = 0.1 ± 0.02
a_6 = –1.08 ± 0.55		
r^2 = 0.96	F = 647	

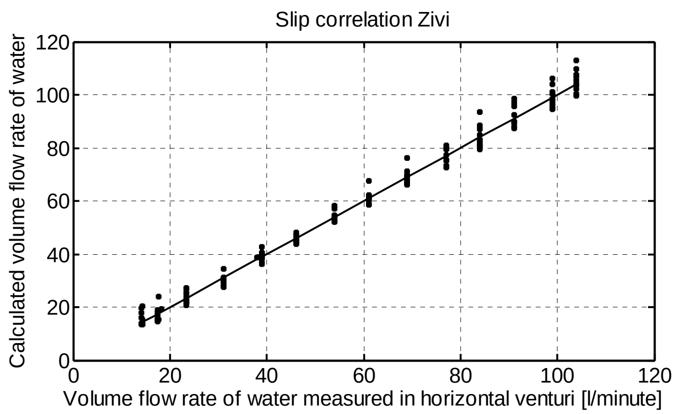

Figure 5 Comparison of measured and predicted water volume flow rates in horizontal flow with the Zivi correlation to predict slip, s.

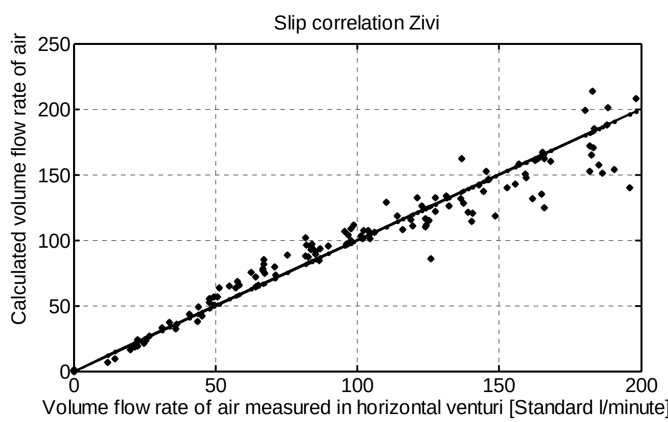

Figure 6 Comparison of measured and predicted air volume flow rates in horizontal flow with the Zivi correlation to predict slip, s.

Table 3 Differences in predicted and measured values of volume flow rates of water and air in a horizontal venturi. Values are independent of slip correlation used

	$S_{\rm abs}$	$S_{\rm rel}$ (%)
$Q = Q_{\rm water} + Q_{\rm air}$, l/m	11	7
$Q_{\rm water}$, l/m	2.9	8
$Q_{\rm air}$, slpm	13	13

Table 4 Coefficients in Eq. (6) to predict the homogeneous void fraction with correction coefficient ξ in combination with the Zivi correlation for the slip; vertical flow

a_{00} = 0.373 ± 0.02	a_{01} = 0.517 ± 0.05	a_{02} = – 0.185 ± 0.08
a_{03} = – 0.261 ± 0.05	a_{04} = – 0.248 ± 0.08	a_{05} = 0.057 ± 0.01
r^2 = 0.966	F = 659	

$$S_{\rm abs} = \sqrt{\left[(1/n)\sum_{i=1\ldots n}(Q_{{\rm exp},i} - Q_{{\rm calc},i})^2\right]} \tag{9}$$

Differences between the relative errors of various slip correlations are less than 1%. The choice of slip correlation does therefore not affect mass flow rate prediction for horizontal flows.

3.3 *Homogeneous void fraction and correction parameter ξ vertical flow*

Similar to the case of horizontal flow (Section 3.2), the homogeneous void fraction, β_α, and the correction parameter, ξ, are to be determined. This section deals with the assessment of these two parameters for the case of vertical flows.

For the homogeneous void fraction, Eq. (6) is again used. The coefficients a_{0j} have been fitted to experimental data (see Table 4). The correlation coefficient, r^2, is high and also the F-statistic is high. Errors indicated are the 78% errors.

For the compensation coefficient ξ, again Eq. (7) is used. The fitting results of the coefficients are for the Zivi correlation given in Table 5. In this case only three coefficients suffice to predict the correction coefficient. For two correlations, the Chisholm and the one of van der Geld, Eq. (8) were employed

The combination of Q and the homogeneous void fraction β_α again yields both individual volume flow rates, $Q_{\rm air}$ and $Q_{\rm water}$. Figures 7 and 8 compare predictions and measurements for both volume flow rates and for the Zivi correlation used for Table 5. The agreement is good, again with some discrepancies at higher flow rates, as explained in Section 3.2.

The errors for all five correlations investigated are compared in Table 6. Differences between the relative errors of various slip correlations are less than 2%. The choice of slip correlation does not affect mass flow rate prediction, therefore, in the case of vertical flows as well.

Table 5 Coefficients in Eq. (7) to predict the correction coefficient ξ in combination with the Zivi correlation for the slip; vertical flow

a_0 = 1.413 ± 0.02	a_1 = 0.3129 ± 0.009	a_2 = – 0.578 ± 0.03
a_3 = 0	a_4 = 0	a_5 = 0
r^2 = 0.944	F = 979	a_6 = 0

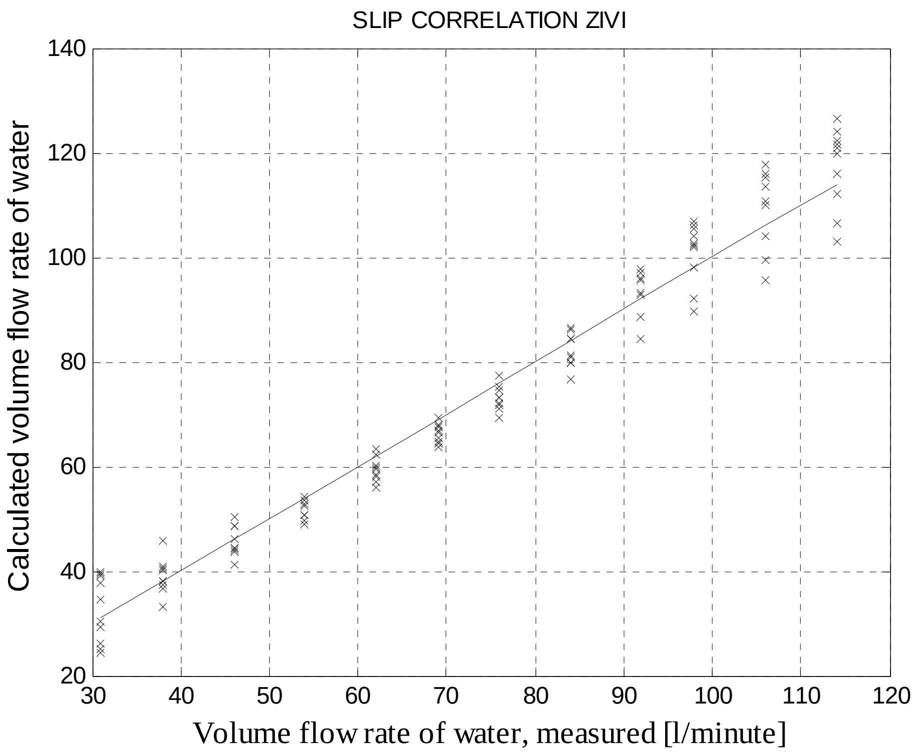

Figure 7 Comparison of measured and predicted water volume flow rates in vertical flow with the Zivi correlation to predict slip, s.

4. MEASURING METHOD SUMMARY

Summarizing, the new measuring method encompasses the following preparatory steps:

1. Mount two pressure differential sensors to a venturi in a pipe through which the two-phase system to be measured is flowing. Mount them upstream and downstream of the throat, as in Fig. 3. Allow the sampling frequency to be 50 Hz or higher for each sensor, and allow measuring times of 2 min or more.

2. Mount an absolute or gauge pressure sensor and a temperature sensor in the flow upstream of the venturi at the same axial height.

Table 6 Differences in predicted and measured values of volume flow rates of water and air in a vertical venturi for various slip correlations used.

	$Q = Q_{\text{water}} + Q_{\text{air}}$ (l/m)		Q_{water} (l/m)		Q_{air} (slpm)	
	S_{abs}	S_{rel}(%)	S_{abs}	S_{rel}(%)	S_{abs}	S_{rel} (%)
Schmidt *et al.*, 2008	7.8	7	2.7	6	11.1	15
Chisholm	7.8	7	2.8	6	11.1	15
Zivi	7.0	6	5.0	8	9.2	13
Thom	6.5	5	4.4	7	9.3	13
Lockhart-Martinelli	7.0	6	5.0	8	9.3	13

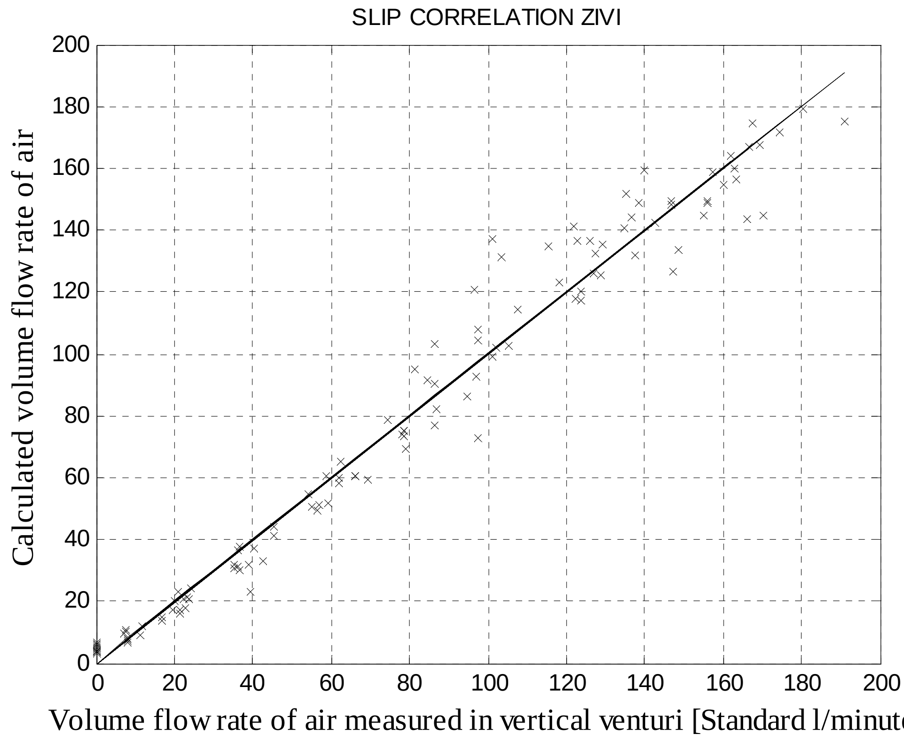

Figure 8 Comparison of measured and predicted air volume flow rates in vertical flow with the Zivi correlation to predict slip, s.

3. Select a slip correlation to work with.

4. Select the functional relationships for f and ξ of Fig. 4 to work with. These are, for example, the function for ξ given by Eq. (7) and the function for β_{α} given by Eq. (6) of the present paper.

5. Determine the coefficients a_{00}, etc., of the functional relationships for f and ξ [see the examples of Eqs. (6) and (7)]. This is done by fitting to experimental data for

which the individual flow rates Q_{air} and Q_{water} are known.

The actual measurement of the individual flow rates of a two-phase flow through the venturi requires the following sequence of steps:

A. Measure the mean value of the pressure drop and the standard deviation of the fluctuations of the pressure drop for each sensor.

B. Compute the values of the parameters x and y used in the functional relationships for f and ξ that have been selected in step 4 above.

C. Use the equation for f to compute β(see Fig. 4).

D. Determine the mass density of the gas according to Eq. (1) from the measured value of the absolute pressure P_P and the temperature t upstream of the venturi.

E. Determine the mass density of the two-phase mixture according to Eq. (5), making use of the results of step C and D and of the slip correlation selected in step 3 above.

F. Determine the value of ξ according to its defining equation with the values of x and y determined in step B.

G. Use the results of steps E and F to determine the value of the total volumetric flow rate Q with the aid of Eq. (2) (see Fig. 4).

H. Determine the individual flow rates Q_{air} and Q_{water} from the values of Q and β.

5. CONCLUSIONS

An analysis method has been presented which is based on the ideas that pressure drop fluctuations are indicative of the flow pattern present, that two-phase flows are redistributed in a venturi in a way that depends of the flow pattern and void fraction, and that the ratio of pressure drops downstream and upstream of the throat, and their variances, depend on the individual mass flow rates of air and water. It has been shown that it is possible to deduce the individual mass flow rates of air and water in a two-phase mixture from measured pressure drops in a horizontal and in a vertical venturi. Residual errors have been shown to be acceptably low, 8 and 13%. The two main parameters used are $x = \sigma_{\Delta Pa}/\Delta P_a$ and $y = \Delta P_b/\Delta P_a$, where the first one, x, is the ratio of the rms of pressure drop fluctuations to the pressure drop. Changing pressure drop equipment hardly affected results, and also various analysis methods (corresponding to varying slip correlations) yield similar results.

Future research will be aimed at optimizing the choice of pressure drops, reducing the differences between predictions and measurements, measurement of wet gas flow regimes at high void fraction, and validation with direct measurement of void fraction distributions with the Tomoflow™ instrument.

ACKNOWLEDGMENT

The first two authors thank Michal Krzysztof Zieba and Marc Willekens for assistance in performing the measurements. They are also obliged to Shell for the donation of measuring equipment and thank the Chinese government for financial support in bringing Dr. He Peixiang to the Netherlands.

REFERENCES

Caudullo, A. (1996), *Flussi Bifase in un Venturimetro*, MSc Thesis, University La Sapienza, Rome, Italy.

Falcone, G., Hewitt, G. F., Lao, L., and Richardson, S. M. (2003), ANUMET: A novel wet gas flowmeter, *The 2003 Soc. of Petroleum Engineers Ann. Tech. Conf. and Exhibition*, Denver, CO, Paper SPE 84504.

van der Geld, C. W. M. (1985), On phase distribution transitions in vertical evaporator tubes, PhD Thesis, Eindhoven University of Technology.

Schmidt, J., Giesbrecht, H., and van der Geld, C. W. M. (2008), Phase and velocity distributions in vertically upward high-viscosity two-phase flow, *Int. J. Multiphase Flow*, **34**, 363.

Shen, W. and Wang, J. (2000), *Flow Meter Design Manual*, China: Mechanical Industrial Press of China, p. 411.

Thorn, R., Johansen, G. A, and Hammer, W. A. (1997), Recent developments in three-phase flow measurement, *Measurement Sci. Technol.*, **8**, 691.

Tutu, N. K. (1982), Pressure fluctuations and flow pattern recognition in vertical two phase gas–liquid flows, *Int. J. Multiphase Flow*, **8**(4), 443.