

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

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Abstract. *The metering of the individual flow rates of gas and liquid in a multicomponent flow is of great importance for the oil industry. A convenient, non-intrusive way of measuring these is the registration and analyzing of pressure drops over parts of a venturi. Because of its importance, quite some attempts were made in the literature, but usually it is mandatory to additionally measure the void fraction. The main goal of the present work is the designing of a reliable measuring method for mass flow rates that only utilizes pressure drop recordings in a venturi. The approach followed consists of measuring flow patterns, void fractions and various pressure drops, and by relating pressure drop fluctuations in parts of the venturi to flow patterns. 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. Void fractions are calculated from established correlations for the slip. Prediction results for a vertical venturi are compared with measurements, with void fractions up to 80 %, residual errors are quantified and the effect of the choice of slip correlation studied .*

Keywords: *Two-phase flow, Venturi, Mass flow rate measurement, Pressure drop fluctuations.*

1. INTRODUCTION

This paper reports the first results of a joint research project, between Brazil, Italy and the Netherlands, of multiphase flow through a venturi. The approach followed consists of measuring flow patterns, void fractions and various pressure drops in tubes and venturis with different diameters. One diameter (21 mm) is measured in Florianópolis (Brazil) and another (40 mm) in Eindhoven (The Netherlands). Eventually the results will be combined with measurements performed in Rome with a 50 mm bore tube. The mean void fraction is measured with special impedance probes. Flow patterns of the air-water system are visually observed. Additionally, in Eindhoven the void fraction distribution is studied in two cross sections with a Tomoflow™ instrument, and the orientation of the test tube will be varied.

The practical goal of the experiments 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. This extension of a well-known method for single-phase flow is not trivial for two-phase flow because of redistribution of flow in the venturi and because of the flow pattern dependency of pressure drops (Thorn *et al.*, 1997). In the present study, measurements are reported that have been performed with a venturi with a circular cross-section and with an inlet diameter of 40 mm and a throat diameter of 20 mm. One gauge pressure and various pressure drops in the venturi have been measured, leading to 8 known pressures all along the venturi. In addition the downstream void fraction has been measured with a so-called Tomoflow™ meter that measures 2-D void fraction profiles in two cross-sections.

The analyzing method is based on the ideas that pressure drop fluctuations are indicative of the flow pattern present, and that the ratio of pressure drops downstream and upstream of the throat depend on the individual mass flow rates of air and water. It is quite well known that conveniently measured pressure drops fluctuate in a way that depend on the flow pattern: in intermittent flows larger fluctuations occur than in bubbly or annular flows. That is why pressure drop fluctuations in a venturi are studied. It is also known that the distribution of void fraction changes in a venturi. For this reason ratios of pressure drop upstream and downstream of the throat are being investigated. The present paper discusses the first successful attempts to deduce individual mass flow rate of air and water from these measured pressure drop parameters.

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. 1. Downstream pressure drops are designated with suffix 'b' and upstream ones with suffix 'a'. Symbol 'P' denotes the location of the gauge pressure measurement. Three different differential pressure drop sensors have been used, with 0.4 % full scale accuracy each. Length L1 is 0.207 m, L2 is 0.0415 m, L3 0.02 m, L4 0.1369 m and length L5 is 0.0332 m. The main pressure drops to be used are those just across the convergent part, named ΔP_{a2} , and that just across the divergent part, named ΔP_{b5} .

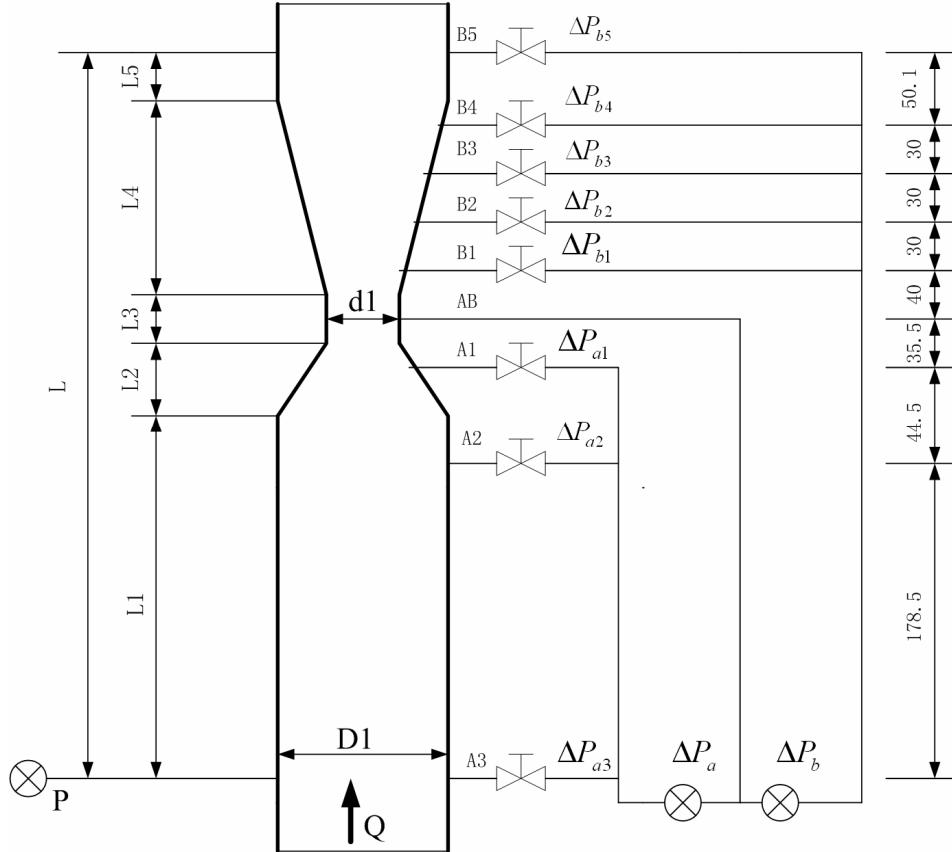


Figure 1. Schematic of the vertical venturi used.

Temperature is measured at one location upstream of the venturi and 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/m³ at pressure 101.325 kPa and temperature 21.1 °C. The mass density of air is calculated at the gauge pressure P_p (kPa) and at temperature t (°C) from:

$$\rho_{air} = 1.2041 \left\{ \frac{273.15 + 21.1}{273.15 + t} \right\} \left\{ \frac{101.325 + P_p}{101.325} \right\} \quad (1)$$

The compressibility of the gas is accounted for in a way described below, see Eq. (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 (40 mm) and d the diameter of the venturi throat (20 mm). The total volume flow rate, in m³/s, is computed with the aid of the following expression:

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

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

venture, zero if flow is zero, and taken to be ΔP_{a2} for the present measurements. Coefficient c is the coefficient of flow rate in the venturi, taken to be 0.995 (Shen, W. and Wang, J., 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:

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

Here τ is the ratio of throat pressure to entry pressure in the venturi, $\tau = P_{AB} / (P_{AB} - \Delta P_{a2})$, 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 attempted:

$$\varepsilon = \beta_a \varepsilon_{air} + (1 - \beta_a) \quad , \quad (4)$$

where β_a denotes the homogeneous void fraction at the inlet, to be determined in a way described below, Eq. (6). 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.* ε_{air} , if applied directly to the gas flow rate only, yields good agreement between measurements and predictions. With the right-hand-side of Eq. (2) used to assess merely the water volume flow rate, Q_{water} , we obtained fitting characteristics that are a little worse than those presented here. For this reason we preferred the assessment of Q rather than Q_{water} only.

The mass density ρ in Eq. (2) is the two-phase flow mass density which depends on the void fraction. Since the latter needs to be predicted in a prediction method for the individual mass flow rates, it has been attempted to use existing, well-established correlations to estimate the actual void fraction. The relation

$$\rho = \{\rho_{air} Q_{air} + \rho_{water} Q_{water} s\} / (Q_{air} + Q_{water} s) = \{\rho_{air} \beta_\alpha + (1 - \beta_\alpha) \rho_{water} s\} / (\beta_\alpha + (1 - \beta_\alpha) s) \quad (5)$$

shows that correlations for the slip, $s = u_{air} / u_{water} = (Q_{air} / Q_{water})(1-\varepsilon) / \varepsilon = \psi (1-\varepsilon) / \varepsilon$, yield estimates for the void fraction once the homogeneous void fraction, β_α is known. Five correlations for the slip in homogeneous flow in straight tubes have been examined to predict void fraction. One of these has recently been developed for high-viscous flows, in work that has been submitted for publication, and will be denoted with “van der Geld *et al.*”. The other names will be quite familiar.

3.2. Homogeneous void fraction and correction parameter ξ

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 , that 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 vertical venturis found to be given by the following polynomial expansion:

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

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

$$x = \sigma_{\Delta P_{a2}} / \Delta P_{a2} \quad , \quad y = \Delta P_{b5} / \Delta P_{a2} \quad , \quad \sigma_{\Delta P_{a2}} = \sqrt{[(1/n) \sum_{i=1 \dots n} (\Delta P_{a2,i} - \Delta P_{a2})^2]}$$

$$\Delta P_{a2} = (1/n) \sum_{i=1 \dots n} \Delta P_{a2,i} \quad , \quad \Delta P_{b5} = (1/n) \sum_{i=1 \dots n} \Delta P_{b5,i} \quad , \quad \sigma_{\Delta P_{b5}} = \sqrt{[(1/n) \sum_{i=1 \dots n} (\Delta P_{b5,i} - \Delta P_{b5})^2]}$$

These are standard ways to compute the root-mean-square of pressure drop fluctuations, believed to be indicative of the flow regime present, see section 1. The ratio of pressure drops measured is presumably dependent on the mass flow rates of water and air, see section 1. 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.

Table 1: Coefficients in Eq. (6) to predict the homogeneous void fraction.

$a_{00} = 0.373 \pm 0.02$	$a_{01} = 0.517 \pm 0.05$
$a_{02} = -0.185 \pm 0.08$	$a_{03} = -0.261 \pm 0.05$
$a_{04} = -0.248 \pm 0.08$	$a_{05} = 0.057 \pm 0.01$
$r^2 = 0.966$	F -statistic = 659

It is important to note that 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 although the measurements were performed at different times.

A similar procedure is followed for the compensation coefficient ξ :

$$\xi = a_0 + a_1 x + a_2 y + a_3 x^2 + a_4 y^2 + a_5 x^3 + a_6 y^3 \quad (7)$$

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. For two correlations, the Chisholm and the one of Van der Geld *et al.*, the following equation has been employed, with x_1 given by $x_1 = \sigma_{\Delta P_{b5}} / \Delta P_{a2}$:

$$\xi = a_0 + a_1 x + a_2 x_1 + a_3 x^2 + a_4 x_1^2 + a_5 x^3 + a_6 x_1^3 \quad (8)$$

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

$a_0 = 1.413 \pm 0.02$	$a_1 = 0.3129 \pm 0.009$
$a_2 = -0.578 \pm 0.03$	$a_3 = 0$
$a_4 = 0$	$a_5 = 0$
$a_6 = 0$	
$r^2 = 0.944$	F -statistic = 979

The combination of Q and the homogeneous void fraction β_α yields both individual volume flow rates, Q_{air} and Q_{water} . Figures 2 and 3 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.

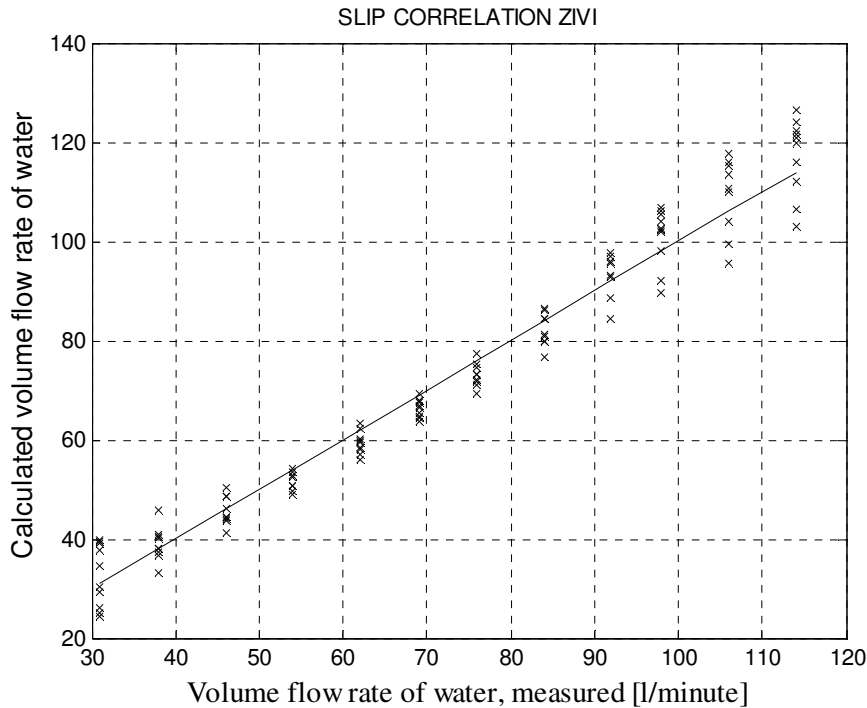


Figure 2. Comparison of measured and predicted water volume flow rates, with the Zivi correlation to predict slip, s .

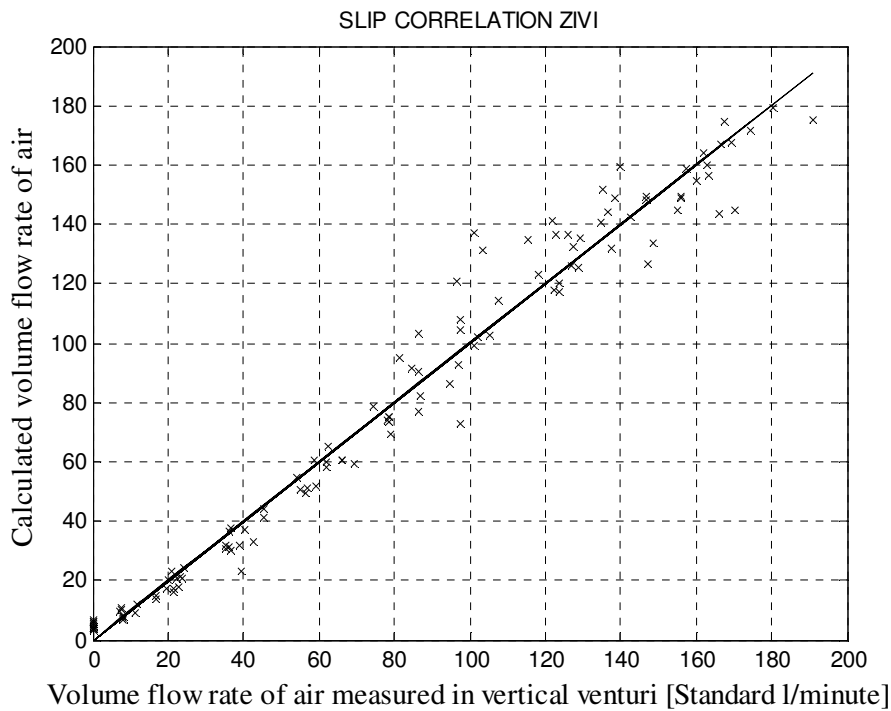


Figure 3. Comparison of measured and predicted air volume flow rates, with the Zivi correlation to predict slip, s .

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

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

No big differences between the various correlations are found.

Table 3: Differences in predicted and measured values of volume flow rates of water and air in a vertical venturi for various correlations for the slip, s .

		S_{abs} (l/min or St l/min)	S_{rel} (%)
$Q = Q_{water} + Q_{air}$ (l/m)	Van der Geld <i>et al.</i>	7.8	6.8
	Chisholm	7.8	6.9
	Zivi	7.0	5.5
	Thom	6.5	5.3
	Lockhart-Martinelli	7.0	5.6
Q_{water} (l/m)	Van der Geld <i>et al.</i>	2.7	5.6
	Chisholm	2.8	5.8
	Zivi	5.0	8.4
	Thom	4.4	7.1
	Lockhart-Martinelli	5.0	8.3
$Q_{air, standard}$ (St l/min)	Van der Geld <i>et al.</i>	11.1	14.5
	Chisholm	11.1	14.5
	Zivi	9.2	12.9
	Thom	9.3	13.2
	Lockhart-Martinelli	9.3	12.9

3.3. Void fraction measurements

The void fraction could not be extracted without a considerably error because the Tomoflow™ sensor was designed for use with oil-water. The void fraction profiles, however, can be checked for time-averaged rotational symmetry in the vertical flow measurements, see the instantaneous examples of Fig. 4. Each time-averaging and averaging over

azimuthal angle give three nontrivial values of $\varepsilon/\varepsilon_{max}$ at three corresponding nonzero radial positions in a cross-section. This is work in progress. Future experiments with oil and air will take full profit of the Tomoflow™ instrument.

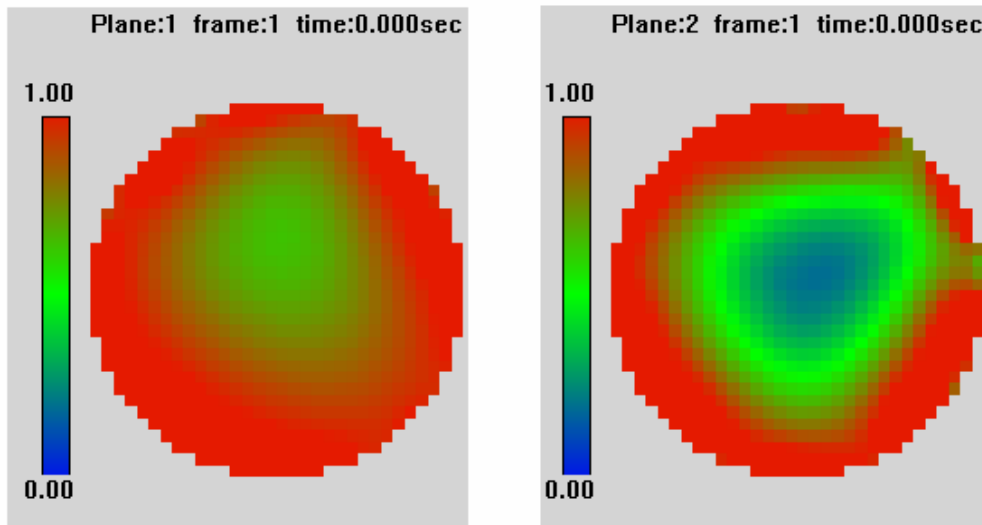


Figure 4. Instantaneous void fraction patterns measured with the Tomoflow instrument in two cross-sections.

4. CONCLUSIONS

An analyzing method has been presented which is based on the ideas that pressure drop fluctuations are indicative of the flow pattern present, and that the ratio of pressure drops downstream and upstream of the throat 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 venturi. Residual errors have been shown to be acceptably low, 6 to 13 %, and nearly independent of the slip correlation used to estimate the void fraction. The two main parameters used are $x = \sigma_{\Delta P_{a2}} / \Delta P_{a2}$ and $y = \Delta P_{b5} / \Delta P_{a2}$, where the first one, x , is the ratio of the root-mean-square of pressure drop fluctuations to the pressure drop. Changing pressure drop equipment hardly affected results.

In the near future it will be investigated whether the correction method for the expansion of the mixture can be simplified, and whether it is possible to discard the correction parameter ξ at all, by adapting the expansion correction method. Tomographic void fraction results obtained downstream of the venturi will be analyzed, and the relation between flow pattern and optimal slip correlation will be investigated. The prediction of pressure drop profiles in a venturi with a four-equation evolution model, see Caudullo (1996), will be further studied.

5. ACKNOWLEDGEMENTS

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