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## TWO-PHASE VIRTUAL FLOW RATE METER: EXPERIMENTAL EVALUATION UNDER INTERMITTENT FLOW

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**Abstract.** Different calibration formulas exist for two-phase flow rate measurement with a Venturi tube. Although these can provide good results for wet gas, their extension to other flow conditions is not obvious. The current work analyzes the accuracy of a virtual flow meter strategy on intermittent flow. This metering framework is derived from one-dimensional analysis of incompressible flow with constant slip in the Venturi tube and uses Chisholm correlation for slip. The analysis is performed with experimental data for air-water flow with Lockhart-Martinelli parameter varying between 0.6 and 2370, corresponding mostly to slug flow. It results that the total mass flow rate is predicted with a root-mean-square deviation of 2.65% and 2.77% for flows in 1" and 2" pipes, respectively, denoting good accuracy. This is a great improvement as compared to the homogeneous model, with equivalent deviations of 12.75% and 12.09%. The applicability of virtual metering techniques is limited, as a precise measurement of mass quality (after separation) is required. Nevertheless, the current results encourage the use of this calibration formula for real two-phase flow rate measurement.

**Keywords:** virtual flow rate meter, two-phase flow, Venturi, intermittent flow

## 1. INTRODUCTION

There are many consolidated technologies for assessing mass flow rate meter of single-phase flows (White, 1998). A well established solution is the differential pressure measurement across a restriction, in which a calibration curve relates the measured values to mass flow rates (ISO5167) (ASME MFC-3M). However, no definite solution exists for flows with more than one phase. If a single-phase calibration curve is naively applied, the unaccounted interaction of the phases implies an underestimation of the multiphase flow rate. A large research effort has been directed at obtaining pressure drop calibration curves for determining two-phase liquid-gas flows, particularly in the flow pattern of wet gas.

In the simplest setup, a homogeneous correction is calculated determining physical properties of a single pseudo-fluid, which are equivalent to the ones of the flow. The homogeneous correction is a simple model with good accuracy for flow patterns with a predominant phase, such as wet gas or dispersed bubbles.

Aiming at wet-gas, Murdock (1962) introduced an Over-Reading (OR) model in which the single-phase gas flow rate is multiplied by an OR factor, larger than one, to adjust for other effects of pressure drop. Murdock's OR is defined with a linear function of the Lockhart-Martinelli factor.

Assuming separated flows, Chisholm (1967; 1977) introduced a correlation for the slip ratio, presenting an OR model in terms of the ratio of the fluids' specific mass and the flow mass quality, embedded into the calculation of the Lockhart-Martinelli factor. De Leeuw (1997) included the effect of the gas Froude number into the OR model, improving prediction accuracy. Other extensions have been suggested, for instance, by Stevens (2002) or Reader-Harris (2009), with varying accuracy depending whether the tested flow parameters are similar to the ones used to calibrate the formulas. Nevertheless, apart from the homogeneous model, the aforementioned formulations were designed for wet-gas flows.

Exploring one-dimensional balance equations, Paz et al. (2010) introduced a formulation for the mass flow rate as function of the specific mass ratio, the mass quality and the slip ratio. It is possible to use Chisholm (1977) correlation to determine the slip in function of the other parameters.

This formulation was used to analyze oil-water-gas flows in a virtual metering system (VMS) for an oil-water-gas flow, mostly in the annular mist flow pattern, for field data in Urucu-AM, Brazil (Campos et al, 2014). In opposition to real metering, in which all flow conditions and fluid properties are measured near the restriction, in a VMS, the measurements near the restriction are complemented with mass quality data obtained, periodically, after a separator test. Though VMS is subject to large errors if there are flow composition fluctuations, the results obtained showed prediction accuracy under 3.5%, for each of the phases volumetric flow rate.

Investigating bubbly flows, Rosa and Morales (2004) introduced a model named algebraic approach, which provides accurate results for liquid dominated flows in which the specific mass ratio is large. This model was recently applied to air-water intermittent flow across a Venturi, with additional measurements of void fraction and gas velocity (Wrasse et al., 2019). In this real metering setup, the authors obtained a prediction accuracy of 6.5% for liquid and 20.6% for gas.

Given that the calibration equation of Paz et al. (2010) was obtained from a theoretical background and is, in principle, not limited to any particular flow pattern, this work intends to verify the prediction accuracy of this formula for intermittent flow. For this purpose, the calibration model will be briefly presented, followed by a description of the experimental data. Next, results for the predicted mass flow rate, gas and liquid superficial velocities in a VMS will be shown and discussed, in comparison with the homogeneous model. Finally, discussions and conclusions close the study.

## 2. MATERIALS AND METHODS

The baseline calibration of two-phase mass flow rate as a function of the pressure drop in a restriction is the homogeneous model. In this setup, the two phases are assumed to flow in a homogeneous mixture, replacing them by a single-phase flow of a pseudo-fluid. From this basic hypothesis, the slip ratio  $S$ , defined in terms of the liquid velocity  $u_l$  and the gas velocity  $u_g$  as

$$S = \frac{u_g}{u_l}, \quad (1)$$

assumes a unitary value for the homogeneous model (Collier and Thome, 1994).

As for the properties of the pseudo-fluid, the specific mass  $\rho$  is calculated in terms of the mass quality  $x$  as

$$\rho_m = \left( \frac{x}{\rho_g} + \frac{1-x}{\rho_l} \right)^{-1} \quad (2)$$

and the mixture viscosity, as

$$\mu_m = \left( \frac{x}{\mu_g} + \frac{1-x}{\mu_l} \right)^{-1}. \quad (3)$$

where the subscripts  $m$ ,  $g$  and  $l$  represent the mixture, the gas phase and the liquid phase.

Having defined the pseudo-fluid, one can use the formula for single-phase flows to predict the total mass flow rate  $W^H$ , defined as

$$W^H = c_d A_t \sqrt{\frac{2\rho_m \Delta p}{1 - \beta^4}}, \quad (4)$$

calculated as a function of the pressure drop  $\Delta p$ , the diameter ratio  $\beta$  (ratio of the throat diameter in the restriction and the duct diameter), the throat cross-section area  $A_t$  and the discharge coefficient  $c_d$ . This discharge coefficient is standardized (ASME, 2004) and is determined in terms of  $\beta$  and the Reynolds number, calculated with the pipe diameter  $D$  as

$$\text{Re}_D = \frac{4W}{\pi D \mu_m}. \quad (5)$$

Finally, each phase superficial velocity is determined in function of the duct cross-section area  $A$  as

$$j_g = \frac{Wx}{\rho_g A} \quad (6)$$

and

$$j_l = \frac{W(1-x)}{\rho_l A}. \quad (7)$$

Next, Paz et al. model assumes a steady separate flow with a constant slip ratio in the converging region of the restriction, with negligible normal viscous and wall shear stress, aside from being incompressible and with no mass transfer effects. Integrating the one-dimensional momentum equation (Paz et al., 2010), it is obtained that

$$W^P = c_d A_t \sqrt{\frac{2\Delta p}{\left(x + \frac{1-x}{S}\right) \left(\frac{x}{\rho_g} + \frac{1-x}{\rho_l} S\right) (1 - \beta^4)}}. \quad (8)$$

Assessing the slip ratio is not an evident task. One alternative is to use the Chisholm correlation, which provides that

$$S_{Chisholm} = \begin{cases} \left(\frac{\rho_l}{\rho_g}\right)^{\frac{1}{4}} & \text{if } \chi < 1 \\ \sqrt{1 + x \left(\frac{\rho_l}{\rho_g} - 1\right)} & \text{if } \chi > 1 \end{cases}, \quad (9)$$

where  $\chi$  is the Lockhart-Martinelli factor, defined as

$$\chi = \frac{1-x}{x} \sqrt{\frac{\rho_g}{\rho_l}}. \quad (10)$$

These models are applied to the database originally presented in Wrasse et al. (2019). These data were acquired in the experimental air-water flow loop located at the Multiphase Flow Research Center, in Curitiba. In this facility, Coriolis mass flow meters are installed before the mixing, in order to provide reference measurements for the single-phase flow rates of air and water, in separate, with a respective uncertainty of 0.5% and 0.1%. The independent line of water feeds one of the horizontal loops, i.e., through manual valves, the flow is directed to the 1" or the 2" inner diameter (ID) flow line. The parallel plate mixers, at the inlet of each horizontal flow line, connect the gas to the liquid lines creating a local stratified air-water mixture, which can evolve to slug flow depending on gas and liquid superficial velocities. This two-phase flow is allowed to develop for 21 meters ( $L/D \approx 808$  for the 1" ID and  $L/D \approx 404$  for 2" ID flow loop) of the horizontal pipe until a Venturi meter is installed. Downstream the Venturi, the fluids flow another 9 meters ( $L/D \approx 346$  for the 1" ID and  $L/D \approx 173$  for the 2" ID flow loop) until they reach a Cyclonic separator, which releases the air to the atmosphere and directs the water back to a reservoir. The whole installation is monitored by a supervisory system, responsible for both the control of the liquid superficial velocity and the data acquisition of the pressure and temperature transducers along the two-phase line. Also, the system acquires data from the differential pressure transducer of the Venturi pipe with an uncertainty of less than 0.5%. The gas superficial velocity is controlled through manual valves. As long as the flow absolute pressure is below 1000 kPa, any combination of liquid and gas superficial velocities is allowed within the range from 0.1 m/s to 4 m/s.

For each pipe diameter, around 160 operation points, defined in terms of the liquid and gas superficial velocities, were established for data acquisition. Figure 1 shows these points in a flow pattern map, indicating that the investigation focuses especially in slug flow. For each data point, three time series of 60 seconds are obtained from all the sensors. The measured values are considered as the average of each time series during the acquisition time. In order to cope with the VMS, in which information of flow composition is obtained in a point of separate single flows, the time series of the reference values for liquid and gas superficial velocities are separated in two sets of equal length—one for test and one for validation. The first set is used to calculate a mass quality  $x$ , as

$$x_i = \frac{W_{gi}^{ref1}}{W_{li}^{ref1} + W_{gi}^{ref1}}, \quad (11)$$

assumed constant throughout the flow as the mass transfer between the phases is negligible in an air-water flow. The second set is kept as reference values, for comparison with the ones predicted by the Venturi calibration models.

The data is such that the largest mass quality values measured are of 2.46% and 4.66% for the 1" and the 2" pipe diameters, respectively. For both cases, the specific mass ratio varies from around 350 to 930. These are translated into Lockhart-Martinelli factors within  $1.34$  and  $2.01 \times 10^3$  for the 1" pipe and within  $0.67$  and  $2.37 \times 10^3$  for the 2" duct.

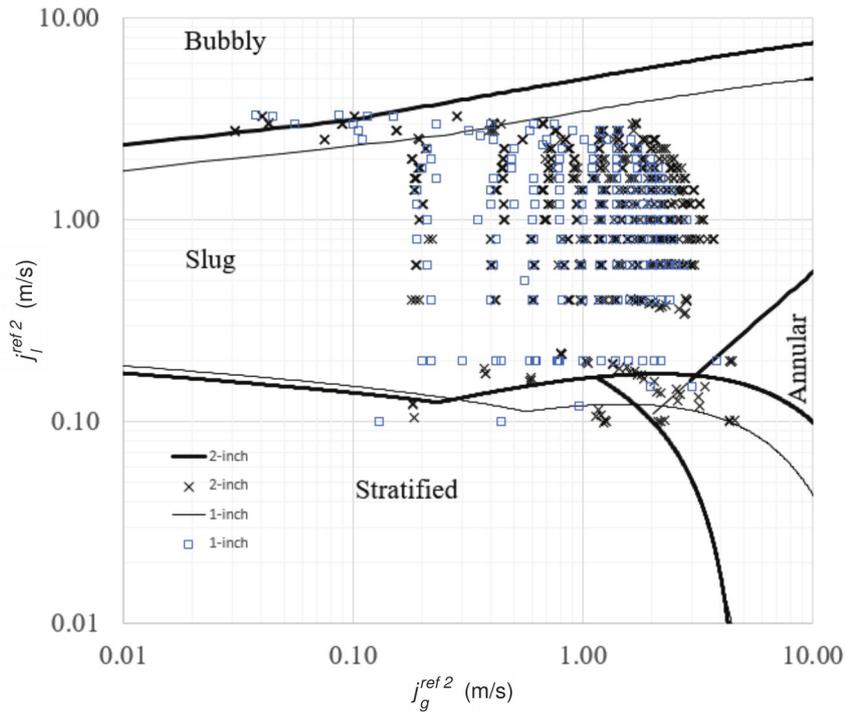


Figure 1: Taitel and Dukler (1976) flow map representing the experimental points for 1-inch and 2-inches pipe ID.

### 3. RESULTS

To provide a visualization of the accuracy of each calibration model, the predicted values for the superficial velocities of liquid and gas are plotted against the reference values, measured before the phase mixing. Figure 2 displays the prediction errors for the homogeneous model analysis of the 1" and the 2" data, with dashed lines portraying a  $\pm 10\%$  deviation.

Homogeneous model (VMS).

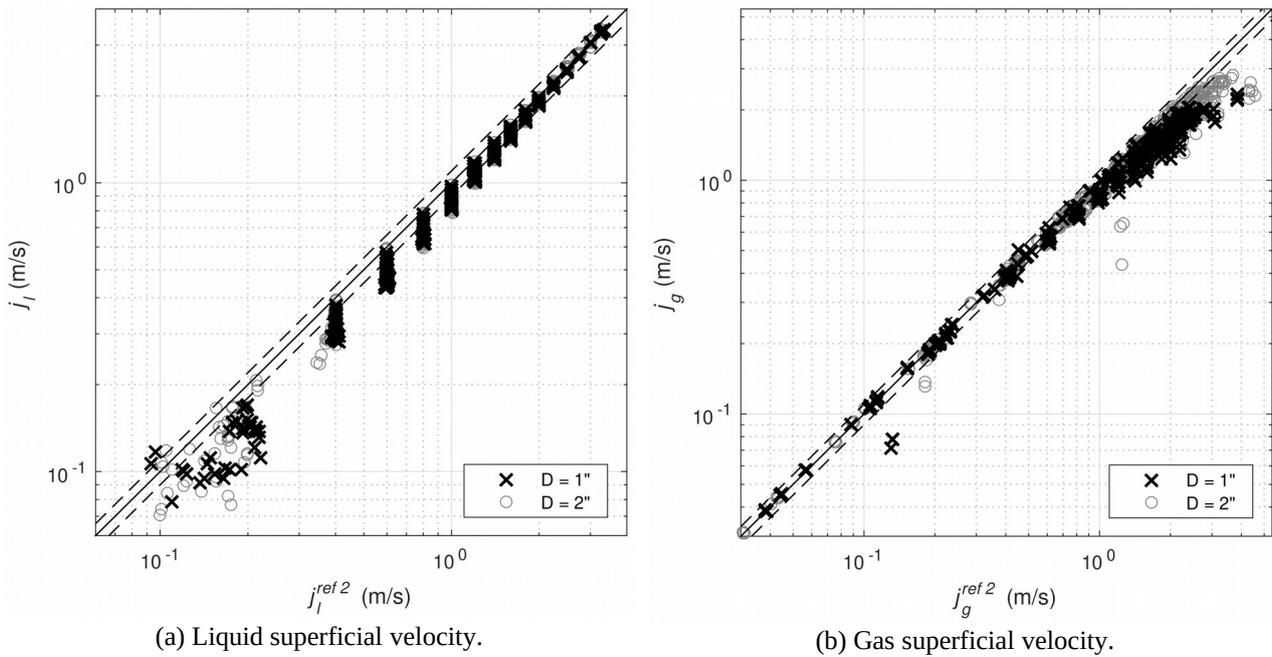


Figure 2: Prediction errors for the homogeneous model in a VMS, with the dashed lines denoting a  $\pm 10\%$  deviation.

Equivalent plots for Paz et al. calibration model are shown in fig. 3, for both pipe diameters. One can notice that, for both models, there are higher deviations for operation points with liquid superficial velocity under 0.3 m/s. This was previously discussed in Wrasse et al. (2019) and is attributed to an instability of the liquid phase in that range, as the installation is not able to provide a steady value of  $j_l$  for the lower end of the tested range. This statement is corroborated as large sample standard deviations are estimated for the measured reference liquid superficial velocities. In that sense, the operation points with  $j_l < 0.3 \text{ m/s}$  are displayed only for qualitative evaluation.

Paz et al. calibration curve (VMS).

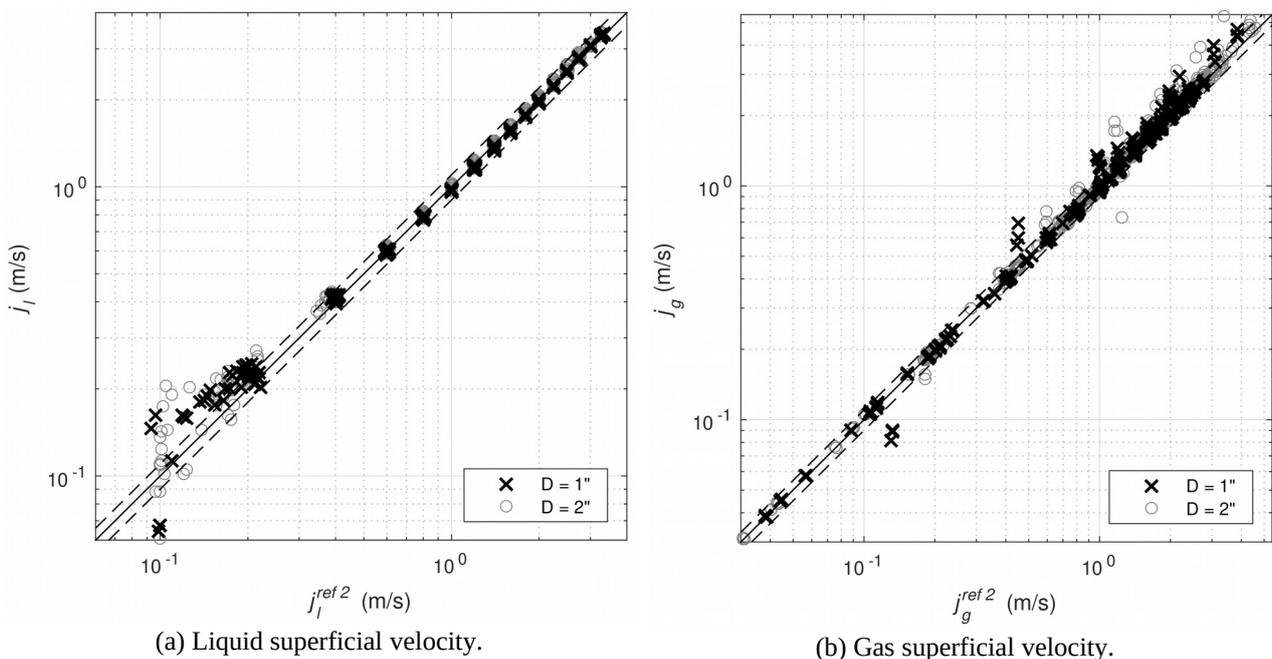


Figure 3: Prediction errors for Paz et al. calibration curve in a VMS, with the dashed lines denoting a  $\pm 10\%$  deviation.

This qualitative analysis is summarized quantitatively with a root-mean-square deviation (RMSD), for each scenario. The RMSD is calculated as

$$\text{RMSD}_{j_g} = \sqrt{\frac{1}{N} \sum_{i=1}^N \left( \frac{j_{g_i} - j_{g_i}^{ref2}}{j_{g_i}^{ref2}} \right)^2} \quad (12)$$

for the gas superficial velocities. The calculation is analogous for the total mass flow rate and the liquid superficial velocities, except that the operation points with  $j_l < 0.3 \text{ m/s}$  are excluded, as they are subject to high process uncertainties. The obtained values are shown in Table 1.

Table 1. Quantitative analysis of prediction errors with different calibration models within a VMS.

RMSD (%)	Homogeneous		Paz et al. model	
	1"	2"	1"	2"
Liquid superficial velocity ( $j_l$ )	12.75	12.09	2.65	2.77
Gas superficial velocity ( $j_g$ )	15.25	15.09	7.58	8.46
Total mass flow rate ( $W$ )	12.75	12.09	2.65	2.77

#### 4. DISCUSSION AND CONCLUSIONS

A comparative analysis of the RMSD values of Table 1 reveals that the model of Paz et al. outperforms the homogeneous model in every evaluation. For the total mass flow rate, for instance, the prediction accuracy is improved by around 10 percentage points. As the examined flows are liquid-dominated and the ratio of specific mass is high, the obtained liquid superficial velocity RMSD values differ from the mass flow rate ones only after the significant digits. The accuracy improvement is smaller for the gas phase, though the deviation is reduced by nearly half.

Although the VMS is not always effective in real setups, as the hypothesis of stable flow composition is not always true, the comparison of two calibration models using the same setup is relevant. Within the VMS strategy, the Paz et al. calibration model provided accurate predictions for the slug flow pattern, with RMSD values below 3% for  $W$  and  $j_l$  and below 8.5% for  $j_g$ .

Considering that similar accuracy values were already obtained when the same calibration model was applied for the annular mist flow regime, the present analysis with slug flow encourages the use of the calibration curve of Paz et al. for a broad range of flow conditions.

For wider applicability, the authors intend to extend the analysis to real measurement setups, with a local evaluation of void fraction.

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