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EVALUATION OF VOID FRACTION PREDICTION METHODS IN SMALL DIAMETER TUBES

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Abstract. *Void fraction of cross section of an internal flow is an important parameter on the analysis of two-phase flow systems. The literature about the void fraction prediction methods presents some lacks about the evaluation of these prediction methods in small diameter tubes (diameters up to 10 mm). This paper focus on evaluation of three void fraction prediction correlation: the homogenous correlation, the drift flux type correlation of Woldesemayat and Ghajar (2007) and the slip type correlation of Tibiriçá et. al (2017). Experimental measures of void fraction of air-water flows in a 7 mm inner diameter and 1.5 m long glass tube using the quick-closing valves (QCV) technique are performed in order to assess which correlations are most suitable. At the end of the study, it is concluded that the Woldesemayat and Ghajar (2007) and the Tibiriçá et. al (2017) correlations could well predict the void fraction in these tubes*

Keywords: *void fraction, two-phase flow, quick-closing valves, air-water*

1. INTRODUCTION

Void fraction in an internal flow is defined as the ratio of the cross-sectional area occupied by the gas and the cross-sectional area of the channel. It is an important parameter for the determination of phases velocity (Li and Carrica, 2018), heat transfer characteristics and pressure drop (Bamardouf and McNeil, 2009), liquid film thickness (Dalkilic et al., 2009), among other characteristics of two-phase flow.

Applications of two-phase flow are commonly encountered in refrigeration and heating applications, chemical plants, pipeline network systems, oil and gas industry, and power generation systems like nuclear and thermoelectric power plants. Therefore, an accurate modeling of two-phase systems is imperative. Correct void fraction estimation, as one of the main parameters to characterize a two-phase, is also essential.

Nowadays, two-phase flow application has been suffering a tendency to become more compact. This process has brought up the necessity of experimental independent data to confirm the performance of void fraction prediction methods in small diameter pipes.

The purpose of this paper concerns on obtaining of void fraction data in tubes with diameters smaller than 10 mm in order to allow the comparison between experimental results obtained with predicted methods mentioned above. Thereby, the best performing correlation in such conditions can be selected.

2. LITERATURE REVIEW

Woldesemayat and Ghajar (2007) pointed out in their paper that most of the void fraction correlations have some restrictions attached to them. Table 1 shows Woldesemayat and Ghajar (2007) void fraction database. It is mainly composed of adiabatic flows in macro-channels.

Table 1. Characteristics of database source of Woldesemayat and Ghajar (2007)

Source	Physical flow configuration/characteristics	Mixture considered	Measurement technique	No. of data points used
Eaton (1966)	Horizontal, ID 52.5 mm and 102.26 mm	Natural gas–water (NW)	Quick-closing valves	237
Beggs (1972)	Horizontal, Uphill (5°, 10°, 15°, 20°, 35°, 55°) and vertical ID 25.4 mm and 38.1 mm	Air–water (AW)	Quick-closing valves	291
Spedding and Nguyen (1976)	Horizontal, Uphill (2.75°, 20.75°, 45°, 70°) and vertical ID 45.5 mm	Air–water (AW)	Quick-closing valves	1383
Mukherjee (1979)	Horizontal, Uphill (5°, 20°, 30°, 50°, 70°, 80°) and vertical ID 38.1 mm	Air–kerosene (AK)	Capacitance probes	558
Minami and Brill (1987)	Horizontal, ID 77.93 mm	Air–water (AW) and air–kerosene (AK)	Quick-closing valves	54 and 57
Franca and Lahey (1992)	Horizontal, ID 19 mm	Air–water (AW)	Quick-closing valves	80
Abdulmajeed (1996)	Horizontal, ID 50.8 mm	Air–kerosene (AK)	Quick-closing valves	83
Sujumnong (1997)	Vertical, ID 12.7 mm	Air–water (AW)	Quick-closing valves	101

Table 2 shows some void fraction measurement techniques.

Table 2. Void fraction measurement techniques

Technique
Quick-closing valves (hold-up)
Sampling (homogeneous flow)
Film Thickness
Acoustic (flow in bubbles)
Impedance (resistance, capacitance, wire mesh)
Radiation attenuation (single and multiple beams of gamma rays, X-ray, neutrons, microwaves, infrared)
Tomography
Pressure drop

Three void fraction prediction correlations are considered and analyzed in this paper, one is the homogenous correlation, which considers gas and liquid phases as a homogeneous mixture flowing with the same velocity, and the two other ones are slip ratio correlations, which assume that the gas and liquid phases are separated with different velocities.

Equation (1) presents the homogeneous model:

$$\alpha = \left[1 + \left(\frac{\rho_v}{\rho_l} \right) \left(\frac{1-x}{x} \right) \right]^{-1} \quad (1)$$

where α is the void fraction, x is the mass fraction of the gas phase, ρ_v is the density of gas phase and ρ_l is the density of liquid phase.

Woldesemayat and Ghajar (2007) evaluated a database of adiabatic flows in macro-channels for different inclinations and adjusted a drift flux correlation to this dataset. The correlation performed better than 68 compared correlations. Equation (2) depicts the correlation:

$$\alpha = \frac{U_{SV}}{U_{SV} \left(1 + \left(\frac{U_{SL}}{U_{SV}} \right)^{\left(\frac{\rho_v}{\rho_l} \right)^{0.1}} \right) + 2.9 \left[\frac{gD\sigma(1 + \cos\theta)(\rho_L - \rho_G)}{\rho_L^2} \right]^{0.25} (1.22 + 1.22 \times \sin\theta)^{\frac{P_{atm}}{P_{system}}}} \quad (2)$$

where U_{SV} is the superficial gas velocity, U_{SL} is the superficial liquid velocity, D is the tube diameter, P_{system} is the fluid pressure, P_{atm} is the atmospheric pressure, g is the gravity acceleration, σ is the superficial tension between the phases and θ is the inclination of the pipe.

Tibiricá et al. (2017) identified and optimized a set of correlations for flow boiling and two-phase flow conditions in micro-channels, among them, a new slip-ratio type void fraction correlation. Equation (3) presents the correlation:

$$\alpha = \left[1 + 1.2364 \times Fr_{\Delta\rho}^{-0.1082} \left(\frac{\rho_v}{\rho_l} \right)^{0.6899} \left(\frac{1-x}{x} \right)^{0.7333} \right]^{-1} \quad (3)$$

Fr is the Froude number, defined by Eq. (4):

$$Fr_{\Delta\rho} = \frac{G^2}{(\rho_l - \rho_v)^2 \times g \times D} \quad (4)$$

where G is the mass velocity of the fluid.

3. TEST FACILITY

The experimental bench was set up to allow void fraction measurements in air-water horizontal flows in a 7 mm inner diameter and 1.5 m long glass tube using the quick-closing valves (QCV) technique, which presents low uncertainty (Qian and Hrnjak, 2019), low cost, easy installation and it is the most common experimental void fraction measurement method - used in investigations of several researchers like Beggs (1972), Elkow and Rezkallah (1996), Sujumngong (1998), and Yashar et al. (2001).

Figure 1 presents a schematic view of the experimental device, which consists of two main systems: a hydraulic system and a pneumatic system. In the hydraulic loop, a hydraulic pump (2) takes water from a large reservoir (1) to a mixer (6) through a silicone hose which passes through a needle valve (3) and a water flow meter (4), allowing, respectively, the control and the measurement of the desired water flow for different experimental conditions. The pneumatic circuit is responsible for transporting compressed gas from an air compressor (7) to the mixer through a needle valve (8) and an orifice plate (9) attached to an absolute pressure sensor (10) and a differential pressure transducer sensor (11). In both systems, retainers (5) are positioned before the mixer to avoid compressed air from entering the hydraulic structure and compromising the water flow measurements as well to prevent water from entering the pneumatic structure and affecting the compressed air flow measurements. In addition, temperature sensors are placed for the water reservoir and room temperature.

Two normally open and one normally closed quick-release valves are operated electronically. The first valve (13) is located upstream while the second valve (15) is located downstream of the glass tube. These two valves are responsible for trapping the air-water mixture in the test tube (14) for analyzing the void fraction, thus they stay open until the flow presents itself in permanent regime for the desired experimental conditions and, at this moment, they are closed simultaneously. The third valve (12), in the bypass circuit, stays open until the other valves are closed, thereby the not-trapped fluid can continue to flow, preventing harmful pressure overload on the experimental equipment.

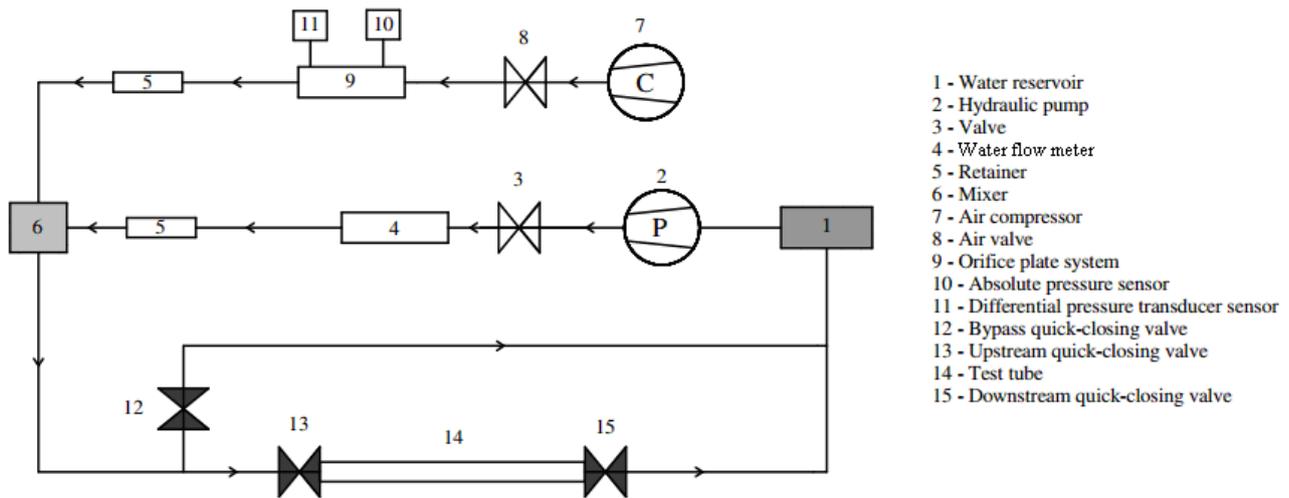


Figure 1. Schematic view of the experimental device.

The compressed air flow is measured using the orifice plate technique. The differential pressure transducer sensor and the absolute pressure sensor provide the necessary parameters to realize the calculation according to the ASME PTC 19.5-2004 standard. Following this standard, a diameter of 1.28 mm was chosen for the orifice plate. The measurement of the compressed air flow using the orifice plate technique was calibrated with an uncertainty of 5%.

The turbine flow meter, responsible for measuring the water flow, was calibrated with an uncertainty of 2%. This uncertainty was evaluated by the method of propagating uncertainties described by Moffat (1988).

The necessary parameters for the calculation of void fraction using the homogeneous correlation, the drift flux type correlation of Woldeamayyat and Ghajar (2007) and the slip type correlation of Tibiriçá et. al (2017), previously mentioned, are obtained by the measuring equipment of the experimental bench.

Experimental data of void fraction is obtained from the calculation of the volume of liquid stored in the test tube, which is performed by measuring the length of water stored in the pipe by the quick-closing valves. The calculus of this data considers that each valve has an internal volume 32 mL, which corresponds to 84 mm in tube length, silicon hoses with 12.7 mm internal diameter were used to connect the glass tube with the solenoid valves. The hose at the inlet is 0.98 cm length while the one at the outlet is 2.5 mm. Experimental void fraction presents a calculated uncertainty of 2%.

4. RESULTS

Experimental measurements were conducted at ambient temperature of 19.1 °C and atmospheric pressure of 94 kPa. The density of water was 998 kg/m³. All observations were conducted on intermittent flow (plug or slug).

Table 3 presents the experimental measurement data, where P_v is the absolute pressure upstream of the orifice plate, Q_v the volumetric flow of compressed air, Q_l the volumetric flow of water air and α_{exp} the measured void fraction.

Table 4 shows the void fraction values calculated for the homogeneous correlation, α_h , the drift flux type correlation of Woldeamayyat and Ghajar (2007), α_w , the slip type correlation of Tibiriçá et. al (2017), α_t , and the experimental void fraction calculation, α_{exp} , according the mass fraction of the gas phase, x , of each experiment.

Table 3. Experimental measurement data range

P_v (kPa)	Q_v (m ³ /s) (10 ⁻⁵)	Q_l (m ³ /s) (10 ⁻⁵)	α_{exp}
100	1.385	2.825	0.3105
102	1.961	2.658	0.3875
103	2.117	2.608	0.4011
103	2.380	2.547	0.4298
105	2.806	2.470	0.4736
109	4.246	2.570	0.5084
114	5.153	2.448	0.5431
122	6.624	2.297	0.5990
123	6.461	2.008	0.6035
130	6.898	1.838	0.6352
133	7.804	2.060	0.6322
141	7.542	1.875	0.6639

Table 4. Experimental calculates values

X	α_h	α_w	α_t	α_{exp}
0.000585	0.3290	0.3387	0.3092	0.3105
0.000898	0.4246	0.3951	0.3737	0.3875
0.000998	0.4480	0.4084	0.3894	0.4011
0.00115	0.4830	0.4284	0.4130	0.4298
0.00142	0.5319	0.4566	0.4467	0.4736
0.00215	0.6230	0.5155	0.5177	0.5084
0.00286	0.6779	0.5498	0.5597	0.5431
0.00419	0.7426	0.5940	0.6131	0.5990
0.00470	0.7629	0.6054	0.6253	0.6035
0.00579	0.7896	0.6237	0.6476	0.6352
0.00598	0.7912	0.6297	0.6550	0.6322
0.00673	0.8009	0.6354	0.6609	0.6639

Figure 2 presents the comparison between the homogeneous correlation, the drift flux type correlation of Woldeamayat and Ghajar (2007) and the slip type correlation of Tibiriçá et. al (2017) with the values measured experimentally.

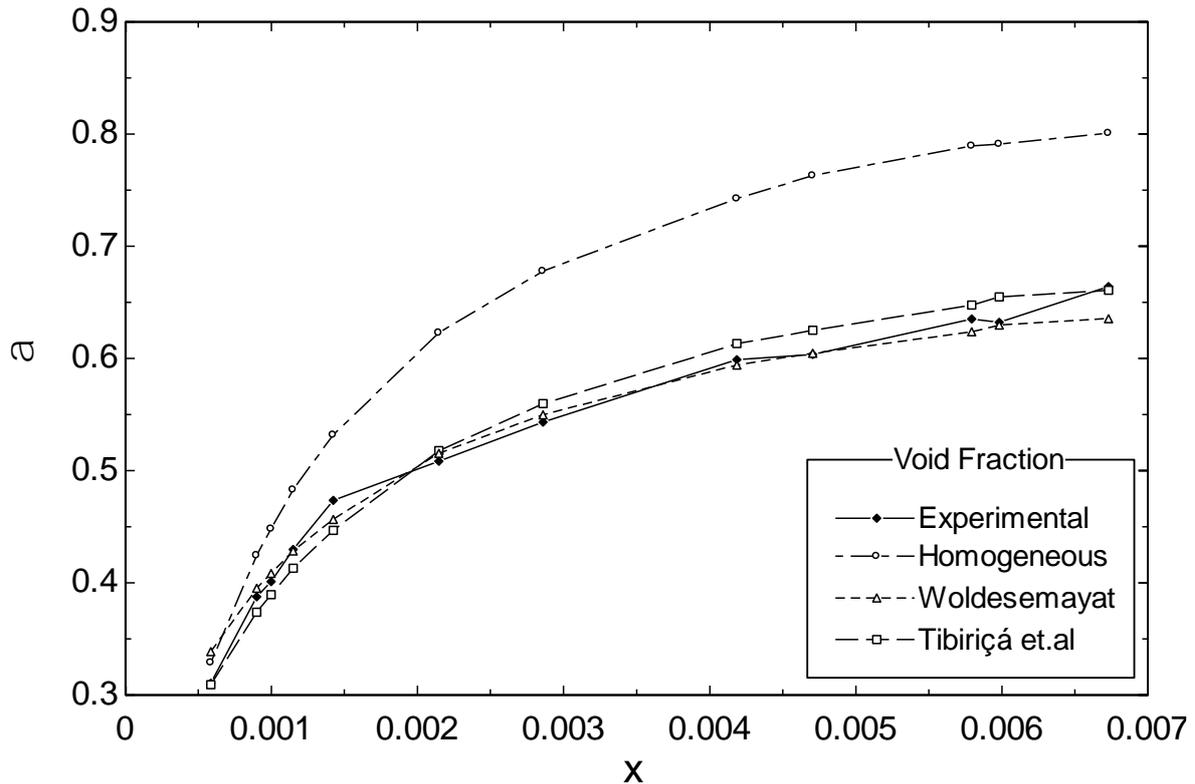


Figure 2. Comparison of void fraction correlations with experimentally measured values

Analysis of the Fig. 2 shows that Woldesemayat and Ghajar (2007) and the correlation of Tibiriçá et. al (2017) follow the experimental behavior for all evaluated vapor title, while the homogeneous correlation presented a good performance only for low mass fraction.

5. CONCLUSIONS

This paper conducted an experimental studied on cross-sectional void fraction. 12 new data points were measured for an adiabatic air-water, horizontal flow, in a 7 mm glass pipe using the quick closing valves method, with experimental uncertainty of $\pm 2\%$. Comparison with literature correlations shows that Woldesemayat and Ghajar (2007) correlation predicts well for the conditions tested, while the homogeneous model overestimated the void fraction. Only intermittent flows were tested.

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