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Void fraction prediction in annular two-phase flow

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ABSTRACT

A new method to predict the void fraction in annular two-phase flow in macroscale and microscale channels is presented. The underlying experimental database contains 2673 data points collected from 29 different literature studies for 8 different gas–liquid and vapor–liquid combinations (water–steam, R410a, water–air, water–argon, water–nitrogen, water plus alcohol–air, alcohol–air and kerosene–air), for tube diameters from 1.05 mm to 45.5 mm and for both circular and non-circular channels. The new prediction method is strongly simplified with respect to most existing correlations, as it depends only on vapor quality and the gas to liquid density ratio and reproduces the available data better than existing prediction methods. Importantly, this study shows that there appears to be no macro-to-microscale transition in annular flows, at least down to diameters of about 1.0 mm.

1. Introduction

Annular two-phase flow is one of the most frequently observed flow patterns in gas–liquid and vapor–liquid two-phase flow systems, such as steam generators, air conditioning and refrigeration systems, chemical processing plants and nuclear reactors. In annular flow, a part of the liquid phase flows as a continuous film that streams along the channel wall, while the rest of the liquid phase is dispersed as entrained droplets in the gas or vapor phase that flows in the center of the channel. Due to its practical relevance, annular flow has been extensively studied in the last decades. Nonetheless, annular flow is still actively investigated as more accurate and reliable prediction methods are required for several cutting-edge applications, such as nuclear reactor fuel optimization and power uprate, nuclear systems transient and safety analyses and micro-evaporators design for the thermal management of computer chips, microelectronic components, laser diodes and high energy physics particle detectors.

One of the most important parameters used to characterize two-phase flows is the cross sectional void fraction ε (simply referred to as the void fraction in what follows) representing the fraction of the channel cross sectional area occupied by the gas or vapor phase. As such, the void fraction is a flow parameter bounded between 0, corresponding to single-phase liquid flow, and 1 corresponding to single-phase gas flow. The accurate prediction of the void fraction is required in virtually any two-phase flow calculation, since it is used as input for determining numerous other key flow parameters, including the two-phase flow density, the two-phase flow viscosity and the average velocities of the two phases. Besides, the void fraction plays a fundamental role in the modeling of two-phase flow pattern transitions, heat transfer and pressure drop. The knowledge of the void fraction is also crucial in many thermal–hydraulic simulations, such as coupled neutronics–thermal hydraulics calculations and two-phase natural circulation loop flow rates and heat transport rates predictions.

Due to its importance, numerous void fraction prediction methods have been proposed so far and several assessments of prediction methods have been published, including the recent contributions by Vijayan et al. (2000), Coddington and Macian (2002), Woldesemayat and Ghajar (2007) and Godbole et al. (2011). According to Vijayan et al. (2000), in particular, the available void fraction prediction methods can be classified into four groups. The first group is given by slip ratio models, which specify an empirical relationship for predicting the slip between the phases. The second group is given by $K\varepsilon_h$ models that predict the void fraction by multiplying the homogeneous model void fraction ε_h with an empirically derived correction factor K. Then, the third group is given by drift-flux correlations, which are based on the Zuber and Findlay (1965) drift-flux model and specify two empirical relations to predict the distribution parameter and the drift velocity. Finally, the fourth group is the so called miscellaneous correlations, which are empirical relations that do not fit into any of the other groups. By far, the majority of the void fraction prediction methods proposed to date are based on the drift-flux model. As a matter of fact, the three most accurate correlations recommended

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in the recent review by Woldesemayat and Ghajar (2007) are drift-flux models.

The purpose of the present study is to present a new void fraction prediction method specifically designed for annular two-phase flow. This new prediction method covers both macroscale and microscale channels, adiabatic and evaporating flow conditions and is strongly simplified with respect to most existing correlations, as it depends only on vapor quality and the gas to liquid density ratio. As will be shown, the new prediction method reproduces the available data better than existing correlations and extrapolates to non-circular channels. This new method is part of a unified annular flow modeling suite that is currently being developed by the authors that also includes methods to predict the axial frictional and total pressure gradients, the annular liquid film thickness, the liquid film and gas core velocity profiles, the convective boiling heat transfer coefficient and the entrained liquid fraction (Cioncolini et al., 2009a, 2009b; Cioncolini and Thome, 2011, 2012). The present method replaces the correlation of Woldesemayat and Ghajar (2007) that has been used previously in this modeling suite.

In what follows, the experimental void fraction databank collected for use here is presented in Section 2. The new void fraction prediction method is described in Section 3, followed by results and discussion presented in Section 4.

2. Experimental database description

The main details regarding the experimental annular flow databank for circular tubes are summarized in Table 1, while a selection of histograms that further describes the collected data is shown in Fig. 1. The database includes 2633 measurements of the void fraction collected from 24 different literature studies that cover 8 different gas–liquid and vapor–liquid combinations (both single-component saturated fluids such as water–steam and refrigerant R410a and two-component fluids, such as water–air, water–argon, water–nitrogen, water plus alcohol–air, alcohol–air and kerosene–air) and 17 different values of the tube diameter in the range of 1.05–45.5 mm, thus spanning from 'micro' to 'macroscale'. Most of the test rigs in the database for adiabatic two-component flows have been designed with calming sections long enough to significantly damp out any dependence on inlet conditions (Wolf et al., 2001), so that inlet effects can be neglected in the present study.

As can be seen in Table 1, 89.3% of the collected data are for adiabatic upflow, while 4.9% are for evaporating upflow and 5.8% cover adiabatic horizontal flow conditions, so that the databank is biased towards adiabatic upflow conditions. Besides, as can be seen in Fig. 1, most of the data were taken at operating pressures below ~2.0 MPa and at mass fluxes below ~1500 kgm^{-2} s^{-1}. As such, additional void fraction measurements are more than welcome, particularly at medium to high operating pressures, high mass fluxes and under evaporating flow conditions.

As noted by Levy (1999), the transition from intermittent to annular flow typically corresponds to a void fraction between 0.7 and 0.8. As can be seen in Fig. 1, all the data collected in Table 1 correspond to a local void fraction above 0.7 and the vast majority of the data are actually above 0.8. As such, the contamination of the data from intermittent flow can be expected to be minimal, and is therefore neglected in the present study.

It is well known that when the hydrodynamic conditions are appropriate the pull of gravity can delay the rise of the liquid phase in vertical upflow conditions, thus affecting the void fraction. A preliminary check of the influence that gravity may exert on the flow can be obtained by extrapolating a criterion proposed by Wallis (1961) for predicting flow reversal, the condition at which in an initially cocurrent annular upflow some of the liquid in the film starts flowing downward under the pull of gravity. This flow reversal condition reads as follows:

$$\sqrt{J_l^*} + \sqrt{J_g^*} < 1 \Rightarrow \text{Flow reversal} \tag{1}$$

Table 1
Experimental annular flow data bank for circular tubes.

Reference	Fluids	d (mm)	P (MPa)	G (kgm^{-2} s^{-1})	x	ε	(1)	(2)	(3)	(4)	(5)
Anderson and Mantzouranis (1960)	H_2O–Air	10.8	0.11	22–1419	0.01–0.70	0.70–0.97	23.5	↑	a	52	QCV
Beggs (1972)	H_2O–Air	25.4; 38.1	0.55–0.68	64–1058	0.04–0.83	0.72–0.98	na	↑	a	13	QCV
Celata and Frazzoli (1981)	H_2O–Steam	21.2	4.9–6.9	170–300	0.19–0.98	0.70–0.98	na	↑	d	118	RA
Alia et al. (1965)	H_2O–Ar	15.0; 25.0	0.60–2.2	306–3000	0.11–0.81	0.70–0.99	60–157	↑	a	265	LD;RA
	Alcohol–Ar										
Dejesus and Kawagi (1990)	H_2O–Air	25.4	0.15	205–1320	0.01–0.12	0.70–0.89	66	↑	a	28	RA
Godbole et al. (2011)	H_2O–Air	12.7	0.12–0.26	93–880	0.01–0.32	0.70–0.90	50	↑	a	57	QCV
Kaji and Azzopardi (2010)	H_2O–Air	19.0	0.15	41–695	0.01–0.67	0.70–0.96	300	↑	a	59	CP
Leung et al. (2005)	H_2O–Steam	13.4	2.0	4500	0.03–0.11	0.73–0.95	na	↑	d	12	RA
Mukherjee (1979)	Kerosene–Air	38.1	0.29–0.61	49–2520	0.02–0.76	0.71–0.98	na	↑	a	39	CP
Spedding and Nguyen (1976)	H_2O–Air	45.5	0.11–0.12	29–1057	0.01–0.93	0.71–0.99	na	↑	a	101	QCV
Sujumnong (1998)	H_2O–Air	12.7	0.11–0.26	64–3260	0.01–0.77	0.72–0.99	na	↑	a	41	QCV
Ueda (1967)	H_2O–Air	19.4	0.11	97–661	0.01–0.05	0.70–0.79	68	↑	a	25	QCV
Shedd (2010)	R410a	1.05; 2.96	1.9–3.1	400–800	0.20–0.96	0.70–0.99	90–114	→	a	152	CP
Silvestri et al. (1963)	H_2O–Ar	25.0	0.60–2.1	280–2900	0.06–0.84	0.71–0.99	60	↑	a	436	FT
	H_2O + Alcohol–Ar										
Adorni et al. (1963)	H_2O–Ar	15.1	0.60–2.1	312–3420	0.06–0.82	0.70–0.98	99	↑	a	121	FT
Casagrande et al. (1963)	H_2O–N_2	25.0	0.29–2.4	255–2880	0.07–0.79	0.70–0.99	60	↑	a	109	FT
	H_2O + Alcohol–Ar										
Cravarolo et al. (1964)	H_2O–Ar	15.1; 25.0	0.60–2.1	266–2880	0.04–0.79	0.70–0.98	60–232	↑	a	517	FT
Alia et al. (1966)	H_2O–Ar	15.1; 25.0	0.60–2.1	266–3290	0.04–0.90	0.70–0.99	140–233	↑	a	136	FT
Gill et al. (1964,1965)	H_2O–Air	31.8	0.11	24–555	0.09–0.94	0.91–0.99	64–171	↑	a	147	FT
Hall-Taylor et al. (1963)	H_2O–Air	31.8	0.11–0.16	34–76	0.41–0.78	0.95–0.98	184	↑	a	18	FT
Whalley et al. (1974)	H_2O–Air	31.8	0.12–0.35	78–789	0.10–0.90	0.91–0.99	590	↑	a	139	FT
Brown (1978)	H_2O–Air	31.8	0.17–0.31	158–316	0.33–0.66	0.94–0.98	420	↑	a	30	FT
Würtz (1978)	H_2O–Steam	20.0	7.0	500–2000	0.20–0.70	0.72–0.96	450	↑	a	18	FT

(1) – Dimensionless distance L/d of test section inlet from mixer (2 component fluids, adiabatic tests only).
(2) – Flow direction: ↑ = vertical upflow; → = horizontal flow.
(3) – Type of test: a = adiabatic; d = diabatic.
(4) – Number of data points.
(5) – Measuring technique: QCV = quick closing valves; RA = radiation attenuation; CP = capacitance probe; LD = liquid displacement; FT = annular film thickness.