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Liquid film circumferential asymmetry prediction in horizontal annular two-phase flow

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ABSTRACT

This study considers the prediction of the degree of asymmetry in the circumferential distribution of the liquid film in the tube cross section of horizontal annular gas–liquid two-phase flow, endemic of the lower region of this flow regime near the stratified-wavy flow transition boundary. Focusing on disturbance waves as the predominant mechanism for transporting the liquid in the annular film from the bottom to the top of the tube to counterbalance the draining effect of gravity, a new prediction method for the degree of asymmetry in the annular liquid film is proposed that outperforms existing correlations. Flow pattern maps for horizontal gas–liquid two-phase flow of frequent use in the design of evaporators and condensers can thus be explicitly updated to account for both symmetric and asymmetric annular flows. The underlying experimental database contains 184 measured liquid film circumferential profiles, corresponding to 1276 local liquid film thickness measurements collected from 15 different literature studies for tube diameters from 8.15 mm to 95.3 mm.

1. Introduction

Annular two-phase flow is one of the most important of the gas–liquid two-phase flow regimes because of the large range of industrial applications in which it occurs, including chemical processing plants, air conditioning and refrigeration systems, and nuclear reactors. Annular flow in horizontal tubes, in particular, is relevant for direct-expansion evaporators, condensers, air-conditioning coils and micro-heat sink design. In annular flow, a part of the liquid phase is transported as a continuous film that streams along the channel wall, while the rest of the liquid phase is dispersed as entrained droplets in the carrier gas core that flows in the center of the channel. Due do their practical importance, annular flows have been extensively investigated in the last decades. Recent interest in these flows is mostly motivated by the need of more accurate and reliable closure relationships required in several cutting-edge applications, such as micro-evaporator and micro-condenser design, nuclear fuel optimization, nuclear reactor power uprates and nuclear systems transient and safety analyses, but also for the more effective thermal-hydraulic design of numerous types of two-phase heat exchangers.

In the lower range of horizontal annular flow, when the flow conditions are appropriate, the liquid in the film tends to drain down the tube walls under the action of gravity, giving rise to an asymmetric liquid film distribution in the channel cross section characterized by a thin liquid film at the channel top and a thicker liquid film at the channel bottom. In particular, the liquid film at the channel bottom can be up to 100 times thicker than the liquid film at the channel top, based on available data. The prediction of the degree of circumferential asymmetry in the liquid film is critical for characterizing and properly segregating experimental databanks for adiabatic, boiling and condensing two-phase flow in horizontal tubes. Axial-symmetric horizontal annular flow data, in fact, can be merged with vertical annular flow data and can be analyzed with axial symmetric annular flow models. Asymmetric horizontal annular flow data, on the other hand, require a dedicated treatment that includes gravity among the parameters that affect the flow and the influence of the local variation of heat transfer around the tube perimeter, reported in numerous experimental studies. Besides, in the design of horizontal evaporators and condensers the prediction of the degree of asymmetry of the annular liquid film can help in selecting the most appropriate design tools or can suggest what design modifications could mitigate the asymmetry or prevent the liquid film from becoming asymmetric.

Starting from available measurements of the circumferential liquid film distribution in horizontal annular flow, the purpose of the present study is thus to present a new prediction method for the degree of circumferential asymmetry of the liquid film. As will be shown, the new prediction method reproduces the available data better than existing correlations and allows updating some frequently used flow maps for horizontal evaporation and

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condensation to explicitly account for both symmetric and asymmetric annular flow regions. This new method is part of a unified modeling suite for annular flow that the authors are currently developing that includes methods to predict the axial frictional and total pressure gradient, the annular liquid film thickness, the liquid film and gas core velocity profiles, the convective boiling heat transfer coefficient, the entrained liquid fraction and the void fraction (Cioncolini et al., 2009a,b; Cioncolini and Thome, 2011, 2012a,b).

In what follows, the horizontal annular flow experimental databank collected from the open literature for use here is presented in Section 2. The new prediction method for the liquid film asymmetry is described in Section 3, followed by results and discussion presented in Section 4.

2. Experimental database description

The main details regarding the horizontal annular flow experimental 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 184 measured liquid film circumferential profiles, corresponding to 1276 local liquid film thickness measurements collected from 15 different literature studies that cover tube diameters in the range of 8.15–95.3 mm. In most of these literature studies the liquid film is assumed to be symmetric with respect to the vertical plane drawn from the top to the bottom of the tube, and liquid film thickness measurements are accordingly performed on one side only of the pipe. A selection of measured liquid film profiles from Table 1 is included in Fig. 2, where the dots represent the actual measurements while the solid line is a cubic spline interpolant. The collected databank is limited to horizontal annular flows, while partially stratified flows where the liquid film is not covering the entire tube circumference are not included. In the study of Williams et al. (1996), the minimum value of the liquid film thickness that could be reliably measured was 60 μm, according to the authors. Measurements below this threshold that are included in the Williams et al. (1996) database are therefore not included in the databank in Table 1. It is worth noting that two liquid film profiles measured by Lin et al. (1986) could not be included in Table 1 due to poor quality of the original figure.

As can be seen in Table 1, most of the collected data are for low pressure air–water flows at room temperature. The variations of the gas to liquid density ratio $\rho_g \rho_l^{-1}$, viscosity ratio $\mu_g \mu_l^{-1}$ and surface tension σ are correspondingly very limited, as can be seen in Fig. 1. Additional measurements with different fluids and operating conditions appear therefore particularly welcome.

Regarding the experiments themselves, when geometric information is provided in the original studies, it can be noticed that the test rigs have been designed with calming sections long enough to significantly damp out any dependence on inlet conditions, so that inlet effects can be neglected in the present study.

Typical measurement errors of the local film thickness range from about 5% to 15%.

In Fig. 1, the ratio of the circumferentially average liquid film thickness t_a to the tube diameter d is in the range of 5.8×10^{-4}–6.5×10^{-2}, while the ratio of the liquid film thickness at the tube bottom t_b to the tube diameter d is in the range of 6.3×10^{-4}–2.0×10^{-1}, so that the liquid film can be considered to be thin compared with the tube diameter, as typically happens with annular flows. In particular, the average liquid film thickness t_a is calculated as the arithmetic mean of the local film thickness measurements provided, counting two times the tube side values when measurements are performed on one side only of the tube.

Furthermore in Fig. 1 the entrained liquid fraction values predicted according to the method of Cioncolini and Thome (2012a) are small for the majority of the data, indicating a mild liquid loading of the gas core and a weak mass coupling between liquid film and gas core. As a consequence, the cross sectional void fraction ε can be estimated assuming a perfect segregation between liquid and gas as follows:

$$\varepsilon \approx \left(1 - 2\frac{t_a}{d}\right)^2 \tag{1}$$

Void fraction values predicted with Eq. (1) are in the range of 0.75–0.99, as shown in Fig. 1.

3. New prediction method

Different parameters have been proposed to quantify the degree of asymmetry in the circumferential liquid film distribution in horizontal annular flow. A simple way to characterize the degree of asymmetry is to use the ratio $t_t t_b^{-1}$ of the film thickness at the tube top t_t to the film thickness at the tube bottom. A drawback of this asymmetry parameter is that the liquid film distribution on the tube side is not taken into consideration, so that $t_t t_b^{-1}$ mostly reflects the variations of the film thickness at the tube bottom. A potentially better asymmetry parameter is the ratio $t_a t_b^{-1}$ of the circumferentially average liquid film thickness to the film thickness at the tube bottom, which takes into account the actual liquid film

Table 1
Experimental annular flow data bank.

Reference	Fluids	d (mm)	P (MPa)	G (kg m^{-2} s^{-1})	x	$t_t t_b^{-1}$	$t_a t_b^{-1}$	L/d[a]	No. points
Sekoguchi et al. (1982)	H_2O–Air	26.0	0.12	88–130	0.32–0.54	0.08–0.48	0.32–0.67	141	4
Fukano and Ousaka (1989)	H_2O–Air	26.0	0.12	76–168	0.30–0.92	0.21–0.67	0.44–0.80	142	6
Paras and Karabelas (1991)	H_2O–Air	50.8	0.11–0.20	69–308	0.21–0.83	0.03–0.80	0.23–0.92	296	10
Nishiyama (1981)	R113	14.0	0.04	163–177	0.12–0.25	0.05–0.06	0.33–0.44	NA	2
Shedd and Newell (2001)	H_2O–Air	12.7; 25.4	0.08–0.09	58–126	0.22–0.84	0.19–0.76	0.60–0.87	200–400	9
Luninski et al. (1983)	H_2O–Air	8.15; 9.85 12.3	0.10	60–448	0.03–0.43	0.06–1.13	0.26–1.09	NA	48
Fisher and Pearce (1978)	H_2O–Air	12.0; 19.1 31.8; 50.8	0.10	188–927	0.03–0.31	0.02–0.41	0.25–0.60	NA	5
Butterworth (1972)	H_2O–Air	31.8	0.10	183–347	0.09–0.13	0.04–0.05	0.29–0.29	NA	2
Hurlburt and Newell (1996)	H_2O–Air	25.4	0.10	65–223	0.12–0.61	0.15–0.54	0.45–0.83	98	5
Jayanti et al. (1990)	H_2O–Air	32.0	0.16–0.24	112–179	0.18–0.50	0.05–0.48	0.40–0.75	109	5
Williams et al. (1996)	H_2O–Air	95.3	0.12	155–183	0.61–0.67	0.23–0.60	0.49–0.72	NA	2
Weidong et al. (1999)	H_2O–Air	40.0	0.10	130–299	0.13–0.29	0.11–0.14	0.43–0.51	130	7
Lin et al. (1986)	H_2O–Air	26.9	0.10	164–201	0.10–0.28	0.03–0.19	0.29–0.44	NA	5
Butterworth and Pulling (1973)	H_2O–Air	32.0	0.25	143–190	0.16–0.44	0.03–0–13	0.27–0.35	122	2
Laurinat (1982)	H_2O–Air	50.8	0.17–0.27	75–1032	0.07–0.96	0.01–0.89	0.16–0.91	300	72

[a] Dimensionless distance L/d of liquid film thickness measuring location from test section inlet.