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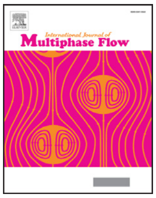

Prediction of symmetry during intermittent and annular horizontal two-phase flows

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ABSTRACT

An optical method is developed for a 2.95 mm inner diameter circular mini-channel to estimate liquid film thicknesses. The greyscale pictures obtained with a high-speed camera are processed to determine the liquid-vapour interface positions for annular and intermittent flows. The experiments are thus performed for a large range of flow conditions. The saturation temperatures tested ranged from 20 °C to 100 °C in steps of 10 °C and the mass velocities are 50, 100, 200, 300 and 400 $\mathrm{kg\,m^{-2}\,s^{-1}}$. A new parameter ranging from 0 to 1, the symmetry, is defined to account for the level of non uniformity of liquid distribution around the tube perimeter. New experimental data are presented (270 data points), that cover a range of symmetry parameter from 0.35 to 1.00. These data are merged with those available in the literature (406 data points with symmetry parameter from 0.71 to 1.00). A sensitivity analysis of the dimensionless numbers of major influence is run and a new correlation is proposed, that enables to predict over 90% of the data points in an error bandwidth of 10%. This correlation is proposed as criterion for asymmetry.

1. Introduction

Two-phase flows occur in a large range of industrial applications corresponding to various domains as chemical processing, petrochemical transportation, evaporators and condensers or steam generators in nuclear plants. The two-phase flow geometry affects the performance of these applications and is strongly linked to inertia, buoyancy, surface tension or shear stresses. All these forces are influenced by the two-phase flow parameters such as vapor quality, mass velocity or temperature but also by the orientation of the flow. In the case of a vertical configuration, gravity being in the two-phase flow direction, the flow is axisymmetric. In the case of a horizontal configuration, gravity being orthogonal to the direction of the flow, the vapor phase tends to move to the top of the channel. Thus, knowledge of geometrical aspects, such as the distribution of liquid around the circumference of the tube, is essential in the understanding of horizontal two-phase flow behaviours.

Studies on film thickness distribution can be motivated by the understanding of heat transfer mechanisms or gas-liquid interface kinematic behaviours such as pumping waves. Different interpretations of the phenomena were proposed to describe the circumferential film distribution. Among them exists the hypothesis of a secondary flow in the gas core, draining liquid to the top of the internal tube wall, promoted by Pletcher and McManus (1965) and then elevated by Laurinat et al. (1984) and Lin et al. (1986). Studies on wave behaviours were also led by Butterworth (1972), Fukano and Ousaka (1989) and Jayanti et al. (1990). The description of hydraulic mechanisms, such as pumping waves, aimed to explain the geometrical configuration, and was related to the evolution of asymmetry with flow parameters.

More recently, a number of studies dealing with asymmetry were carried out, using different formulations of vapour Froude number, as a tool to correlate data. For instance, Williams et al. (1996), Hurlburt and Newell (1997), Schubring and Shedd (2009) and Cioncolini and Thome (2013) proposed various correlations. Williams et al. (1996) observed the evolution of the two-phase flow asymmetry as a function of gas velocity. Most asymmetric flows occur for low gas velocities and the flow tends to be symmetric for high gas velocity. Hurlburt and Newell (1997) proposed a liquid film asymmetry correlation and a liquid film thickness distribution model based on stratified-annular, asymmetric and symmetric annular flows. One of the purposes of Schubring and Shedd (2009) study was to model the base film thickness and to quantitatively link this parameter with the symmetry by the medium of a modified vapour Froude number. This study was led with very slightly stratified two-phase flows. Cioncolini and Thome (2013) considered a new prediction method

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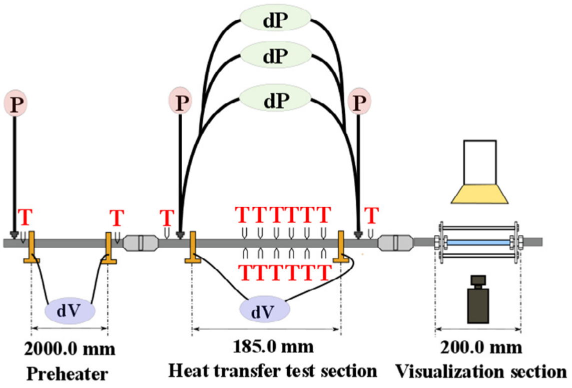

Fig. 1. Schematic of the test section (Charnay et al., 2014).

of asymmetry and developed a flow-pattern map which enables to discriminate asymmetric and symmetric two-phase flows. Hurlburt and Newell (1997), Schubring and Shedd (2009) and Cioncolini and Thome (2013) all described the asymmetry by means of eccentricity which considers a ratio of film thicknesses along the tube circumference.

More recently, Donniacuo et al. (2015) introduced a new definition of eccentricity which was linearly linked to the position of vapour core centre and consequently was based on the difference between the top and the bottom film thicknesses. The eccentricity was qualitatively linked with the flow parameters and commented not only with vapour Froude number but also with Bond number. This last dimensionless number enabled to show the effect of capillary forces on asymmetry, forces which occur for lower diameters than in previous studies.

In the present study, the optical method and the numerical method are presented. They derived from that of Donniacuo et al. (2015) and were used and adapted to build the experimental database. This adaptation enables to study horizontal annular and intermittent flows. In the second part, a new symmetry parameter is presented. It is based on vapour core centre, which is a way to describe the qualitative behaviour of the flow asymmetry in the present case. Then, the present database is described, analyzed and a comparison among previous asymmetry correlations against the present database and existing data in literature is presented with statistical indicators. The limited accuracy in predictions of the available predictive methods lead to the presentation of a new correlation, preceded by the description of the method used for its derivation. This new prediction method is compared to both present databases and an existing one from literature.

2. Presentation of the experimental database

2.1. Description of the experimental test bench

The test bench, designed and previously described by Charnay et al. (2014), enables to set the pressure, the enthalpy and the mass velocity conditions at the inlet of the visualization section. The test section presented in Fig. 1 consists in three parts, consisting of a 2000 mm spirally shaped preheater, a 185 mm horizontal evaporator and a 200 mm glass visualization tube. The preheater ensures the control of the vapour quality at the test section inlet. The vapour quality and the saturation pressure of the glass tube are evaluated at the outlet of the evaporator by assuming the pressure drop and the heat losses as negligible. The test section is presented in Fig. 1.

An optical measurement technique was developed to measure the two-phase flow liquid film thickness in the 2.95 mm inner diameter glass tube (Donniacuo et al., 2015). A high-speed camera system and a light behind the tube enable the visualization of the flow by recording frame sequences. The camera enables to get the local liquid film thickness with a mean resolution of 200 pixels.mm^{-1}.

In each condition of temperature, mass velocity and vapour quality, 4 series of 1363 frames are taken, corresponding to a total time of 2.7 s. The frame size is of 1024 × 1024 pixels and each pixel has a greyscale value ranging from 0 to 255.

A Matlab program was conceived and enables to determine the local film thickness for annular flows (Donniacuo et al., 2015). This method based on greyscale analysis was improved to be applied to intermittent flows where the single-phase profiles have to be detected. This method also enables to sensibly reduce the uncertainty on the interface detection for the annular parts. Since the direct measurement suffers from the refraction effects through the glass of the tube, a correction factor has been introduced:

$$t_{real} = \frac{t_{app}}{Sc \times EF} \tag{1}$$

with t_{app} the apparent film thickness, t_{real} the real film thickness, EF the enlargement factor due to optical deformation, and Sc the scaling factor.

The uncertainty on the apparent film thickness is ± 2 pixels. At each operating condition, the top and bottom liquid film thicknesses were calculated as the average value from 5452 recorded frames. The uncertainty of each measurement is calculated, taking into account several sources of uncertainty: the inner and outer diameter dimensions, the variation of liquid R-245fa refractive index with the temperature and the limitations of image resolution due to finite pixel dimensions. The combined uncertainty for film thickness measurement was evaluated. In the present study, the uncertainty on the apparent film thickness is equal to 2 pixels, the enlargement factor uncertainty is 0.047 and the scaling conversion uncertainty is 0.84 mm/pixel. All these uncertainties were measured for an outer apparent diameter of 909 pixels. As a conclusion, the uncertainty on the estimation of the real top film thickness ranges between 0.02 mm and 0.03 mm depending on the experimental conditions.

2.2. New experimental data points

The experiments are performed with R-245fa for mass velocities equal to 50, 100, 200, 300 and 400 kg m^{-2} s^{-1}, and for saturation temperatures ranging from 20 °C to 100 °C in steps of 10 °C. This range of temperature enables to have important variations of the thermophysical properties as densities, viscosities and surface tension. These variations of saturation conditions change the relative effect of the different forces acting on the two-phase equilibrium. It strongly affects the liquid-vapour interface and then the flow pattern. The large vapour quality range enables to get the transition between intermittent and annular flow.

The variations of the two-phase flow geometry can be first characterized by considering the evolution of the film thicknesses at the top and at the bottom sides of the tube for various saturation temperatures T_{sat} and a given mass velocity G of 200 kg m^{-2} s^{-1} (Fig. 2). It is shown that both film thicknesses decrease with vapour quality. The top film thickness is about ten times lower than the bottom film thickness. Contrarily to the top film thickness, the bottom film thickness clearly increases with the saturation temperature.

The evolution of the film thicknesses affects the symmetry of the flow. It is possible to evaluate the evolution of the two-phase flow symmetry by considering the parameter s which is defined as:

$$s = \frac{d_{top}}{r} \tag{2}$$