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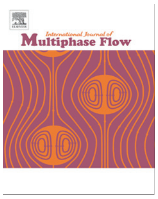

Measurement of liquid film thickness in micro tube annular flow

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ABSTRACT

Heat transfer in micro scale two-phase flow attracts large attention since it can achieve large heat transfer area per unit volume. At large flow rate and high quality, annular flow becomes one of the major flow regimes in micro two-phase flow. Heat is transferred by evaporation or condensation of the liquid film, which are the dominant mechanisms of micro scale heat transfer. Therefore, liquid film thickness is one of the most important parameters in modeling the heat transfer phenomena. In the present study, time averaged annular liquid film thickness is measured by laser confocal displacement meter (LCDM), and the gas–liquid interface profile is observed by a high-speed camera. Glass tubes with inner diameters of $D = 0.3$, 0.5 and 1.0 mm are used. Degassed water and air are used for working fluids, and the total mass flux is varied from $G = 100$ to 500 kg/m^2 s. Flow patterns are observed and flow pattern map based on Reynolds numbers of gas and liquid flows is suggested. Pressure drop is measured and compared with the prediction using Lockhart and Martinelli parameter. Pressure drop is well predicted with Lockhart–Martinelli correlation. Dimensionless mean film thickness is then plotted against quality, and compared with the annular film model assuming flat gas–liquid interface. Flat interface model overestimated the experimental data. It is considered that the shear stress on the gas–liquid interface in the real annular flow is larger than that estimated in the ideal flat interface model. Prediction using new empirical correlation considering the effect of the non-flat gas–liquid interface showed good agreement with the experiment data.

Introduction

Heat transfer in micro tube attracts large attention since it has many advantages, e.g., high efficiency, miniaturization, and stabilization of gas–liquid interface. In micro tubes, flow characteristics are quite different from those in macro tubes, since surface tension becomes dominant in micro scale. At high quality, annular flow is one of the major flow patterns, and film evaporation or condensation dominates the heat transfer in micro tubes. Therefore, liquid film thickness plays an important role in micro scale heat transfer, and many studies concerned with film thickness and interface profiles in annular flow regimes have been conducted.

Schubring and Shedd (2008) investigated liquid film thickness in horizontal annular air–water flow using the diffused light pattern reflected from the liquid surface. Working fluids were air and water. Glass tubes with inner diameters of 8.8 mm and 15.1 mm were used as test tubes. It was reported that the wave velocity of annular film was well correlated by the gas friction velocity. This indicated a direct link between wave velocity and wall shear stress.

Hazuku et al. (2008) measured liquid film thickness in glass tube with inner diameter of 11 mm using laser confocal displacement meter. The data from this method agreed with that from the image processing method. They concluded that the liquid film thickness decreases due to the density change of the gas phase.

Okawa et al. (2010) also investigated film behavior in annular two-phase flow using laser confocal method. They introduced steam-water two-phase flow in heated SUS tube with inner diameter of 12 mm. They controlled total mass flux and heat flux to produce flow oscillation. They concluded that mean film thickness in the thin film region tends to increase with the decrease of oscillation period.

Revellin et al. (2006) measured flow pattern characteristics in micro tubes with inner diameter of 0.5 mm. Working fluid was R-134a and they applied direct current to heat the SUS tube. They measured bubble frequency and superficial vapor velocity by laser light intensity method. In their research, flow patterns and their transitions (bubbly/slug flow/semi-annular flow) were detected by bubble frequency analysis.

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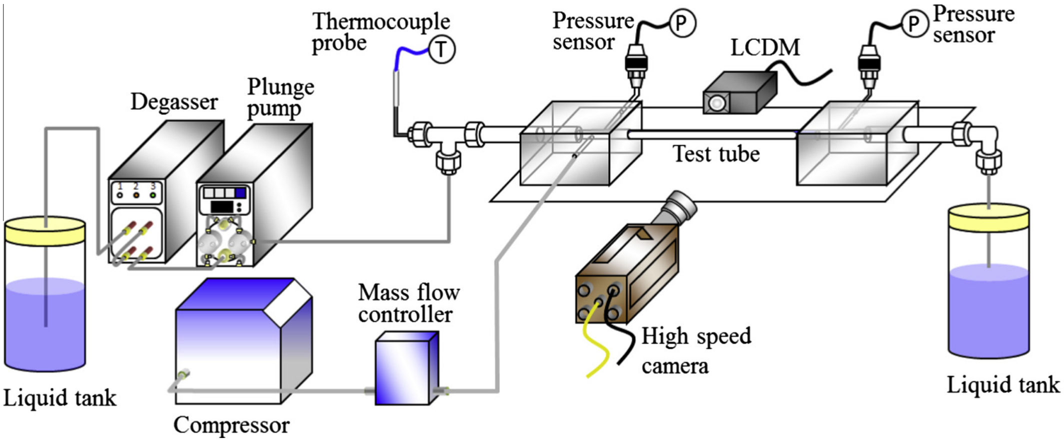

Fig. 1. Schematic of the experimental setup.

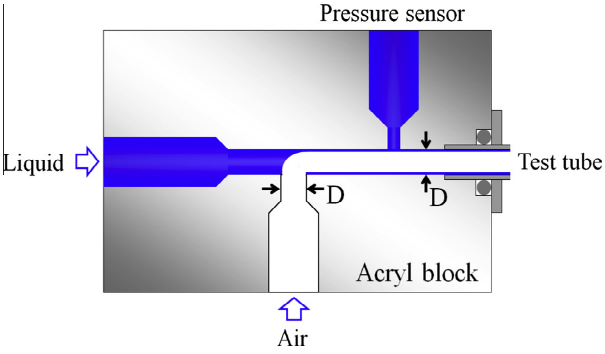

Fig. 2. T-junction in the inlet block.

Han and Shiakzono (2009a) measured liquid film thickness in micro tube slug flow by the confocal method. They used glass tubes with inner diameters of 0.3, 0.5, 0.7, 1.0 and 1.3 mm as test tubes. Working fluids were water, ethanol, and FC40. They proposed an empirical correlation for the dimensionless liquid film thickness based on capillary, Reynolds and Weber numbers. They concluded that no inertial force effect is observed at small capillary numbers, while Reynolds number effect becomes apparent at large capillary numbers.

Tibriça et al. (2010) reviewed measurement methods of liquid film thickness in micro scale. They pointed out that the confocal method allowed dynamic measurements of extremely thin film, and its use should be worth considered for future studies.

Although many researches for liquid film thickness have been carried out, quantitative data of annular liquid film especially in micro scale are still limited. To predict the heat transfer coefficient in micro scale two-phase flow, it is important to clarify the relationship between flow regime and liquid film thickness in micro tube annular flow. In the present study, time averaged liquid film thickness is measured using a confocal method and flow regimes are observed in micro scale annular flow. The relationship between film thickness and flow characteristics is investigated.

Experimental setup and procedures

The experimental setup used in the present study is shown in Fig. 1. Compressed air and degassed water from the syringe pump were introduced to the inlet block and they were mixed at the T-junction. Then, two-phase gas–liquid mixture was introduced in the test tube. Pressure was measured at the inlet and outlet blocks.

Circular glass tubes with inner diameters of 0.3, 0.5 and 1.0 mm were used. Length to diameter ratio was fixed as $L/D = 300$. Both ends of the glass tube were connected to the inlet and outlet blocks. The T-junction in the inlet block is shown in Fig. 2.

Fig. 3 shows the test section and the measurement position. The total length L is defined as the distance from the inlet pressure port to the outlet pressure port. Liquid film thickness and flow regime were measured at the position $0.833L$ downstream from the inlet pressure port.

Mass flow controllers (MQV9200, MQV0005, MQV0050, Yamatake) were used to control the gas flow rate, and syringe pump (IP7100, Lab-Quatec) was used to control the liquid flow rate. Liquid was drawn from the reservoir tank through 20 μm or 60 μm filters. Pressure sensors (AP-10S, AP-13S, Keyence) were used to measure the pressure drop of the test tubes.

Air was used for the gas phase and water was used for the liquid phase. All experiments were conducted under the condition of room temperature. Table 1 shows the properties of water and air under atmospheric pressure.

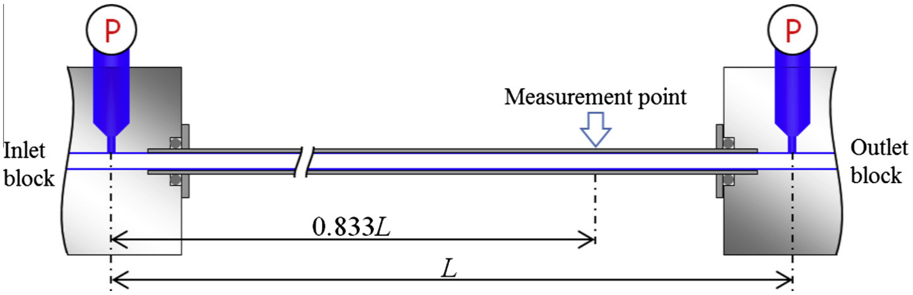

Fig. 3. Test section and the measurement point.