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TWO-PHASE FLOW PATTERNS IN A SQUARE MICRO-CHANNEL

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ABSTRACT

A new set of experimental data of two-phase air-water flow patterns in a square micro-channel is presented. The channel has a cross-section of 1×1 mm^2 and a length of 300 mm. The ranges of the gas and liquid superficial velocities are 0.1–10 m/s and 0.2–7 m/s, respectively. Bubble, bubble-slug transitional, slug, and frothy patterns are observed. The present data are compared with other experimental data reported in the literature, and a good agreement is obtained. It is also compared the present data with those obtained from reduced gravity experiments, in which the Bond number has the same order of magnitude. Some problems associated with the micro-scale modeling of microgravity two-phase flow are also discussed.

INTRODUCTION

Two-phase gas- or/and vapor-liquid flows are of great interest to the design of active thermal control system, power cycle, storage and transfer of cryogenic fluids, and other systems for spacecraft. Reliable design of such systems requires a thorough understanding of the mechanism of two-phase flow at microgravity conditions, such as the phase distributions (the flow patterns), the pressure drops and the heat transfer coefficients at different gas and liquid flow rates. These requirements of space applications have stimulated studies on two-phase flows in reduced gravity conditions in the past decades (McQuillen *et al*. 1998; Zhao, 1999).

The ideal location to conduct these studies is aboard a space station (Zhao *et al*., 2000, 2001a) or in an orbiting space shuttle (Reinarts *et al*., 1995). However, due to the high cost and limited accessibility, most of the experiments on two-phase flow at reduced gravity conditions are performed using some ground-based facilities such as drop tower and parabolic aircraft (Zhao, 1999). There exist some drawbacks to these ground-based experiments. For example, the residual accelerations less than $0.01g_0$ are difficult to maintain on board parabolic aircraft. Here g_0 denotes the gravity at sea level, while g denotes the local or residual gravity. The g-jitters of comparable order are often experienced. The overlord of near $2g_0$ and the rapid change in gravitational fields before and after each reduced gravity portion can induce undesired system transients. The very limited test duration (typically 20 seconds) makes it difficult to eliminate these transient effects. Moreover, for reasons of safety, only certain fluids can be used. The cost is still high by comparison with tests in a static facility on Earth.

Micro-scale modeling on Earth (Galbiati & Andreini, 1994) is an inexpensive way to anticipate the behavior of two-phase flow at microgravity conditions and to help define needs for space or aircraft tests. The idea in this scale modeling is to reduce the impact of gravity and increase that of surface tension forces. The ratio between these two forces is the Bond number $Bo = \Delta\rho g d^2/\sigma$, where $\Delta\rho=\rho_L-\rho_G$ denotes the difference between the liquid and gas densities, d and σ denote the characteristic length (usually the tube diameter) and the surface tension, respectively. Thus, reducing the diameter by a factor of 10 will result in reducing the Bond number by a factor 100, a change equivalent to reducing gravity by a factor 100 as in an aircraft experiment.

On the other hand, capillary gas-liquid two-phase flow also occurs in increasingly more modern industrial applications on Earth. Studies generally confirm significant differences between capillaries and large channels, with respect to flow patterns (Suo & Griffith, 1964; Oya, 1971; Barnea et al., 1983; Damianides & Westwater, 1988;

Fukano & Kariyasaki, 1993; Barajas & Panton, 1993; Triplett *et al*., 1999a; Bi *et al*., 1999), pressure drop (Inasaka *et al*., 1989; Lin *et al*., 1991; Fukano & Kariyasaki, 1993; Fouran & Bories, 1995; Triplett *et al*., 1999b), and boiling heat transfer and critical heat flux (Inasaka *et al*., 1989; Peng & Wang, 1993). Criteria for determining the maximum channel diameter for channel orientation-independent (or, equivalently, gravity- independent) flow have also been proposed by Suo & Griffith (1964), Brauner (1990), Brauner & Moalem-Maron (1990, 1992), and Fukano & Kariyasaki (1993). Zhao *et al*. (2000) found that the gravity-independent criterion developed on the base of the experiments of two-phase gas-liquid flows at different gravity conditions aboard the Russian Mir Space Station is the same as that proposed by Brauner & Moalem-Maron (1992), namely the Bond number is no more than a critical value of an order of 1.

However, due to the extreme complication of two-phase flow, some other dimensionless parameters, for example, the Reynolds number $Re = \rho Ud/\mu$ which may be defined for the two-phase mixture or for each phase alone, should also play an important role in the flow. Therefore, prudence is needed in interpreting the experimental results of the scale modeling. In the present paper, a new experiment of two-phase air-water flow patterns in a square micro-channel is performed. The experimental results are compared with those obtained at reduced gravity conditions, in which the same order of the Bond number is maintained. They are also compared with relevant flow pattern transition models, and some problems associated with the micro-scale modeling are discussed.

EXPERIMENTAL TECHNIQUES

A schematic diagram of the experimental facility is given in Fig. 1.

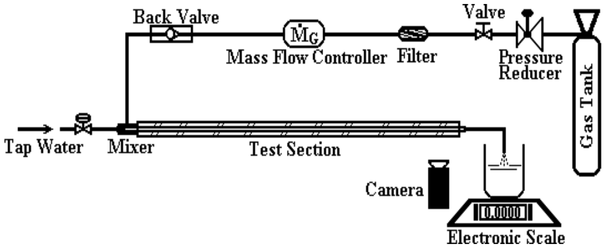

Fig. 1. Schematic diagram of the experimental facility

Fresh tap water and air were used as the experimental mediums. An electronic scale with a range of 0–1.0kg and an accuracy of 10^{-5}kg was used to measure the flow quantity in certain duration (typically 200 seconds), which was measured using a stopwatch with an accuracy of 0.2 seconds. Air was stored in an 8-liter compressed air tank. After the pressure regulator the air pressure was reduced to 0.5MPa. The outlet of the pressure regulator was connected to a mass flow controller. Two mass flow controllers, which have respectively range of 0–0.06 SLM (standard liters per minute) and 0–0.6 SLM, were used to measure the flow rate of the gas phase. The accuracy is 1.5% FS (full scale) for both mass flow controllers.

A Pyrex glass prism was milled to form the square shaped channel along the length of the test section. A flat strip of Pyrex glass was used to create another side, or face, to the square shaped channel. The cross-sectional area of the channel is 1×1 mm^2. Its error was estimated to be within ±8%, which is major resource of the uncertainties of the measured superficial velocities of the gas and liquid phases.

A mixer is located before the test section. It is a cross component through which the test section passes. In the mixing chamber, gas flows into the test section through four holes, which are 0.7 mm in diameter, perpendicular to the channel. The distance between the mixer outlet and the outlet of the test section is 300 mm. The test section is horizontal with respect to the gravity.

Prior to experiments, the test loop was carefully leak-tested with the highest liquid and air flow rates imposed to the system. After all leaks were eliminated, experiments were performed by imposing a nearly constant flow rate of tap water, while varying the flow rate of air. All experiments were performed at ambient temperature and near the atmospheric pressure.

The flow patterns in the test section were identified visually with the aid of a digital video camera recorder (SONY DCR-TRV900E). The camera was always targeted at the test section center. In order to eliminate the image blur, the highest shutter speed of the camera, namely 1/10000 second, was adopted in all experimental runs. The distance between the point pictured by the camera and the mixer outlet was well over 200 channel “equivalent”, or hydraulic, diameters everywhere. The entrance influence may be considered to be negligible, and the flow patterns observed may thus be considered to be fully developed.

FLOW PATTERN OBSERVATIONS

Four flow patterns, namely bubble, bubble-slug transitional, slug, and frothy flows, are observed in the present experiments, in which the ranges of the gas and liquid superficial velocities (U_{SG} and U_{SL}) were 0.1–10 m/s and 0.2–7 m/s, respectively. The characteristics of these flow patterns are shown in Fig. 2, respectively. Flows are all from the top to the bottom in the figure. Note: flows are all horizontal with respect to the gravity in fact.

Bubble flow characterized by distinct bubbles, occurs in relatively small gas superficial velocity. The shapes of the gas bubbles are not always spherical ones, but the equivalent diameters of the gas bubbles are always smaller than the side length of the test channel. With increasing U_{SG} (which leads to increasing the void fraction), the gas bubbles became crowded and their sizes increased, which eventually led to the development of the slug flow.

Slug flow is characterized by elongated cylindrical bubbles with smooth interfaces. For those near the bubble-slug transition boundary, the length of most gas bubble is only slightly bigger than the side length of the test channel. The nose of these bubbles always has slightly pronounced conical shape along the flow direction, while the rear remains the spherical shape. Small gas bubble can still be observed in these flows. Parameter changes leading to higher void fraction (e.g. increasing U_{SG} or/and decreasing U_{SL}), lead to longer bubbles, while small, axisymmetric disturbances may exist in the interface. At much higher U_{SG}, the rear of the elongated bubbles will lose its s spherical shape firstly. Large, non-axisymmetric disturbances will appear in the interface at even higher U_{SG}.

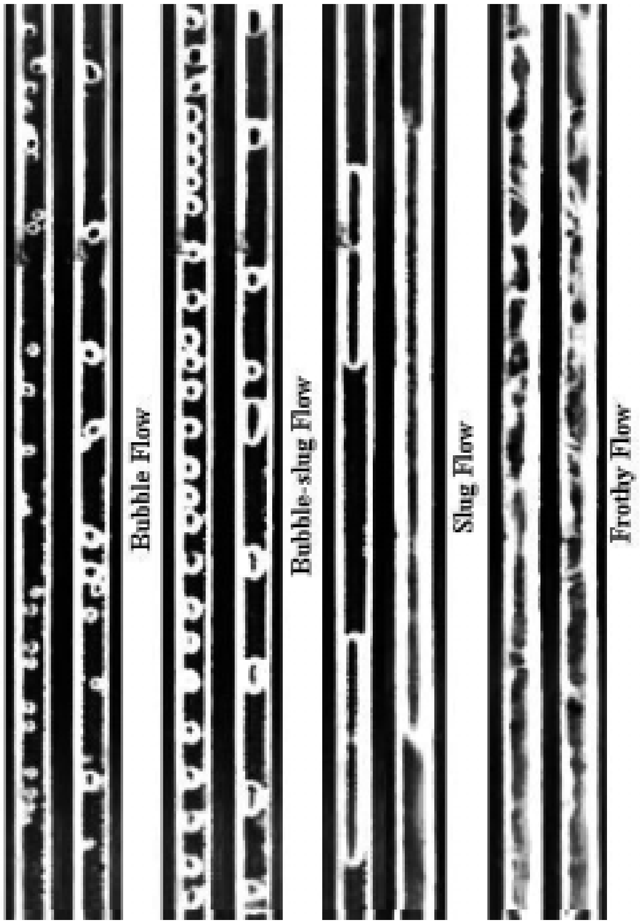

Fig. 2. Typical flow patterns observed in the micro-channel

Frothy flow occurs at much higher U_{SG}. The interface between the gas and liquid phases becomes more irregular and disruption always occurs. Some frothy structures, which result in some dim shadows, appear occasionally in the test channel. It is firstly observed in the present experiments that the liquid phase can form irregular drops moving along the top or bottom side (maybe the corner) of the test channel.

There is also bubble-slug transitional flow identified in several experimental runs. In these flows, most of the gas bubbles are smaller than the side length of the channel while elongated gas bubbles with the length not more than one and a half times of the side length of the test channel can also be observed infrequently. The interval between two elongated bubbles is relatively much large.

According to the above observations, a flow pattern map is presented in Fig. 3.

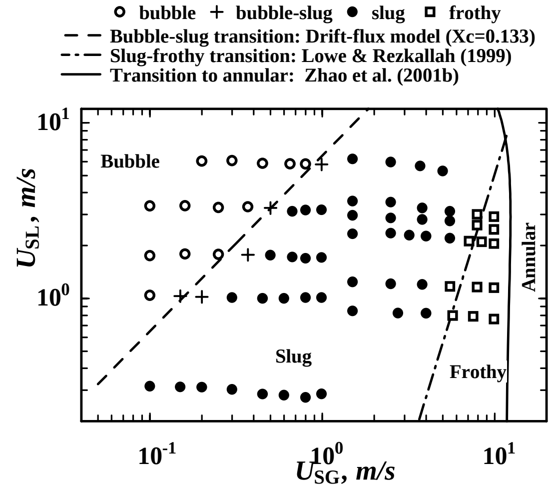

Fig. 3. Flow pattern map

DISCUSSION

Firstly, we compare the observed bubble-slug transition boundary in the present experiment with those of Triplett *et al.* (1999a) obtained with their 1.1 mm-hydraulic diameter circular and semi-triangular test sections (Fig. 4). It shows a relatively good agreement, which indicates that there may exist no influence of the cross-sectional shape on this transition.

Based on the comparisons made by Triplett *et al.* (1999a), *i.e.* Fig. 10 and 11 in their paper, the present data are also consistent with those of Fukano & Kariyasaki (1993) obtained with their 1 mm-diameter circular test section, while large differences will be found between the present data and those of Damianides & Westwater (1988). The inconsistencies associated with the identified flow patterns, which can be inferred from the denominations of flow patterns used by different authors, may be part of the reasons resulting in these differences.

The most frequently used model for predicting the bubble-slug transition in normal size channel at microgravity conditions is the drift-flux model (Dukler *et al.*, 1988; Colin *et al.*, 1996), which can be expressed as following,

$$U_{SL}=U_{SG}(1-Xc)/Xc \qquad (1)$$

where $Xc=C_0\varepsilon_{cr}$ is the transitional quality, C_0 and ε_{cr} are the gas phase distribution parameter and the critical void fraction, respectively. There are two empirical correlations for the transitional quality, which were proposed by Colin et al. (1996) and Jayawardena *et al.* (1997) based on the same database of two-phase flows in normal size channel at microgravity conditions. Detailed comment on them can be found in Zhao (1999). Here, for the later citation, only the correlation of Jayawardena et al. (1997) is given as following,

$$Xc = K\eta/(K\eta + Su^{2/3}) \qquad (2)$$

where K=464.16 is an empirical constant, $\eta=\nu_G/\nu_L$ denotes the ration between the kinetic viscosity of the gas and liquid phases, and $Su=\rho_L\sigma d/\mu_L^2$ is the Suratman number.

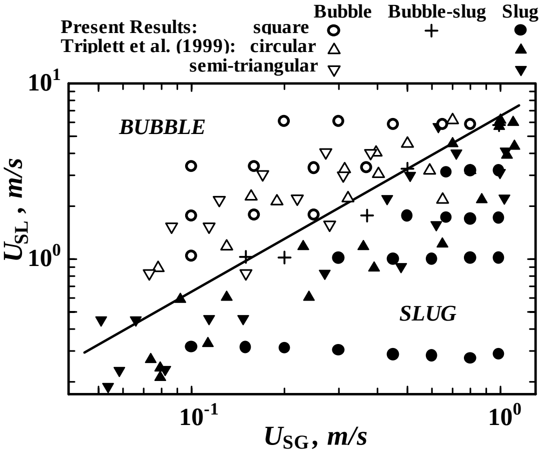

Fig. 4 The bubble-slug transition boundary

Assuming the drift-flux model is still active in capillary two-phase flows, a value of 0.133 for the transitional quality Xc can be obtained from the present experimental data (Fig. 3 or 4). This value is much smaller than those obtained at microgravity. For example, a value of 0.44 for the transitional quality Xc was obtained by Zhao et al. (2001b), which also satisfy the empirical relationship proposed by Jayawardena *et al*. (1999). The experiments of Zhao *et al.* (2001b) were performed in a square channel with a cross-section of 12×12 mm^2 aboard the Russian IL-76 reduced gravity airplane. The value of the Bond number is about 0.58 in the flight experiment, while Bo=0.136 in the present experiment. They are of the same order, under which two-phase flows are gravity-independent. According to the correlation of Jayawardena *et al.* (1997), a value of 0.8 should be taken for the transitional quality in the present study, which is much more than 0.133, the value based on the experimental data.

The difference between the experimental values of the transitional quality in the two cases may indicate that there should be different mechanisms underlying the bubble-slug transition in the capillary two-phase flow and two-phase flow in normal size channel at microgravity conditions. Thus, micro-scale modeling could not be an effective way to anticipate the behavior of (at least) the bubble-slug transition in normal size channel at microgravity conditions.

The present experimental data for higher gas superficial velocity are also in satisfactory overall agreement with similar experimental data report in the literature, when inconsistencies associated with the identified flow patterns are removed. However, it can't be concluded that there isn't influence of the cross-sectional shape on the flow patterns and their transitions due to the subjectivity of the flow and/or flow transition identification used in the present study and others. Methods that can accurately and objectively determine the flow patterns are highly desirable.

The present experimental data are compared with the prediction of the semi-theoretical Weber number model proposed by Zhao & Hu (2000) and modified by Zhao *et al.* (2001b) to conclude the shape influence of the test section (Fig. 3). It has been verified that the predictions of this model are in good agreement with the data obtained from the two-phase flow experiments at reduced gravity conditions and the micro-scale or/and neutral-buoyancy modeling at normal gravity environment. No contradiction between the prediction and the present experimental data is observed. However, since no annular flow was observed in the limited ranges of the flow rates of two phases, the actual transition to the annular flow, which will occur in the same system for larger gas superficial velocities, was not obtained in the present study.

The boundary between the slug flow and the frothy flow determined experimentally by Lowe & Rezkallah (1999) is also plotted in Fig. 3. The value of the Bond number in their study is about 0.36. It shows that this transition line is close to the slug-frothy transition boundary observed in the present study. It may indicate that the micro-scale modeling can be used to anticipate the behavior of the two-phase flow with high flow rates in normal size channel at microgravity conditions. Further studies, however, are still needed in order to make correct interpretation of the results of the modeling.

CONCLUSIONS

A new set of experimental data of two-phase air-water flow patterns in a square micro-channel is presented. The channel has a cross-section of 1×1 mm^2 and a length of 300 mm. The ranges of the gas and liquid superficial velocities are 0.1–10 m/s and 0.2–7 m/s, respectively. Four kinds of flow patterns, namely bubble, bubble-slug, slug, and frothy flows, are observed. The experimental results are compared with the similar experimental data reported in the literature, as well as those obtained in another square channel with a cross-section of 12×12 mm^2 at reduced gravity conditions. In the latter case, the value of the Bond number is of the same order as that in the present study. It has shown that the micro-scale modeling can be used to anticipate the behavior of the two-phase flows with high flow rates in normal size channel at microgravity conditions, while it may be not an effective way for those with low flow rates (or, in other words, the bubble-slug transition).

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