Two-Phase Flow in Vertical Circular Micro-Channel

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Abstract

Two-phase air-water flow in a vertical micro-channel is experimentally investigated. A fused silica channel, 320 mm long, with an inner diameter of 0.53 mm is used as the test section. The test runs are done at superficial velocities of gas and liquid ranging respectively from 0.375 to 21.187 m/s and 0.004 to 2.436 m/s. By keeping the water flow rate constant at a pre-selected value and increasing the air flow rate by small increments, the two-phase flow pattern and pressure drop data are obtained. According to the flow visualization results, five different flow patterns, i.e. slug flow, throat-annular flow, churn flow, annular flow and annular-rivulet flow, are observed in this work. The two-phase pressure drop measured in the experiments includes friction, gravitation, fluid acceleration and sudden contraction terms. However, the frictional pressure drop is found to dominate over the other three components. The frictional pressure drop increases with increasing superficial gas velocity or superficial liquid velocity. The results also illustrate that churn flow experiences relatively high pressure drop in comparison to the other observed flow regimes.

Keywords*:* Micro-channel; Two-phase flow; Flow pattern; Void fraction; Pressure drop

1. Introduction

Two-phase flow in micro-channel flow passages has been studied over the years. The clarifications of micro-scale effects on two-phase flow and heat transfer characteristics have become more necessary due to the rapid development of microstructure devices used for several engineering applications including medical devices, high heat-flux compact heat exchangers, and cooling systems of various types of equipment such as high performance micro-electronics, supercomputers, high-powered lasers. It is obvious that a comprehensive understanding of the trends and parameters dominating flow behavior in mini- and micro-channels is still lacking. Thus, fundamental heat transfer and flow characteristics problems encountered in the development and processing of micro-electronic-mechanical-systems (MEMS) have become a significant challenge in the design and control of these micro-systems.

Two-phase flow and heat transfer characteristics in small channels such as micro-channels and mini-channels are likely to be strongly dependent on surface tension effects in addition to viscosity and inertia forces, resulting in significant differences in two-phase flow phenomena between ordinarily sized channels and small channels. Several investigators have proposed criteria to address the definition of a micro-channel. Recently, Mehendale et al. [1] employed the hydraulic diameter as an important parameter for defining heat exchangers and Kandlikar [2] proposed criteria for small flow channels used in engineering applications.

In the past decade, there have been a relatively small amount of publications available for both mini-channels and micro-channels compared to those for ordinarily sized channels.

Triplett et al. [3,4] studied adiabatic two-phase air-deionized water (DI water) flow characteristics in micro-channels with hydraulic diameter ranging from 1.1 to 1.5 mm. The flow patterns observed were bubbly, slug, churn, slug-annular and annular. The measured void fraction and two-phase pressure drop in the relevant flow regimes were also investigated. The void fraction data were obtained, based on the image analysis.

Serizawa et al. [5] investigated the visualization of the two-phase flow pattern in circular micro-channels. The flowing mixture of air and water in channels of 20, 25 and 100 μm in diameter and that of steam and water in a channel of 50 μm in diameter were conducted experimentally. Two-phase flow patterns obtained from both air-water and steam-water flows were quite similar and their detailed structures were described. The study confirmed that the surface wettability had a significant effect on the two-phase flow patterns in very small channels.

Chung and Kawaji [6] performed an experiment in order to distinguish two-phase flow characteristics in micro-channels from those in mini-channels. Four different circular diameters ranging from 50 to 526 μm were employed to examine a scaling effect on nitrogen-DI water two-phase flow. The results including the flow patterns, void fraction and two-phase pressure drop were analyzed.

The applicability of several widely used viscosity models to the pressure drop prediction of air-water flow through a 0.53 mm diameter channel was examined by Saisorn and Wongwises [7]. The other relevant models for the two-phase flow pressure drop prediction in micro-channels were also examined by Kawahara et al. [8], Chung and Kawaji [6], Saisorn and Wongwises [9 - 11], and Triplett et al. [4].

According to the above discussions, recent studies mainly explored the two-phase flow characteristics in horizontal micro-channels. However, the important information corresponding to the vertical orientation is still lacking. The present work is therefore carried out to study flow pattern and pressure drop characteristics during two-phase air-water flow in a vertical micro-channel having a diameter of 0.53 mm

2. Experimental apparatus and procedure

The experiments were carried out using the apparatus along with the instruments as shown in Fig. 1. The corresponding details are described as follows. Fig. 1 illustrates a schematic diagram of the test facility. Air and water are used as working fluids in the system. Instead of a conventional pump, which may contribute to pulsation and fluid contamination, air and the liquid-filled tank are combined and operated as a pneumatic pump to supply a constant flow rate of liquid through test section. The mixing chamber is designed to introduce the air-water mixture smoothly along the channel. The mixture flows freely from the channel outlet where atmospheric pressure is realized. The gas flow rates are able to be measured by four sets of rotameters within the range of 5-50 sccm, 0.05-0.5, 0.2-2.0, 1-10 SCFH, respectively. For liquid flow rate measurements, an electronic balance (320 $\pm$ 0.001 g) is used to measure the weight of the liquid flowing freely from the outlet over a time. The test section used in this work is fused silica tube having inside diameter of 0.53 mm with length of 320 mm and vertical upward flow is performed during the experiments. The single-phase and two-phase pressure drops across the test section were determined by two pressure transducers installed at the channel inlet. The low range pressure transducer was calibrated from 0 to 400 kPa with a ± 0.8 kPa accuracy and the high range one was calibrated from 0 to 1000 kPa with a ± 2 kPa accuracy. Type T thermocouples are used to measure fluid temperatures. The degree of uncertainty of the temperature measurements was ± 0.1°C.

The detailed formation of each flow pattern is registered by precise stereozoom microscope mounted together with a camera system having shutter speeds of 1/15 to 1/10,000 s and a frame rate of 30 frames per second. According to the above system, a magnified image of up to 60 times can be obtained. In this study, however, the magnification is adjusted so that the appropriate view field (L/D = 10) is obtained. The region near the channel outlet is always selected as the viewing window available for the captured image. An adjustable light source consisting of 150 watt halogen lamp and dimmer is placed under the test section to provide illumination for the flow visualization.

The single-phase flow experiments with different fluids were the first to be performed. Following this, the two-phase flow experiments were conducted at various gas and liquid flow rates. In this work, the gas flow rate was increased by small increments, while the liquid flow rate was kept constant at a pre-selected value. The system was allowed to approach steady conditions before the fluid flow rates, flow patterns and pressure drops were recorded.

3. Results and discussion

3.1 Two-phase flow pattern

Visual observation shows that different flow patterns may occur with gas-liquid co-current flow in a vertical micro-channel. The observations are carried out using visualization system mainly including stereozoom microscope and high-speed camera. The superficial velocities of gas and liquid vary from 0.375 to 21.187 m/s and 0.004 to 2.436 m/s, respectively. By keeping the water flow rate constant at a pre-selected value and increasing the air flow rate by small increments, typical photographs are

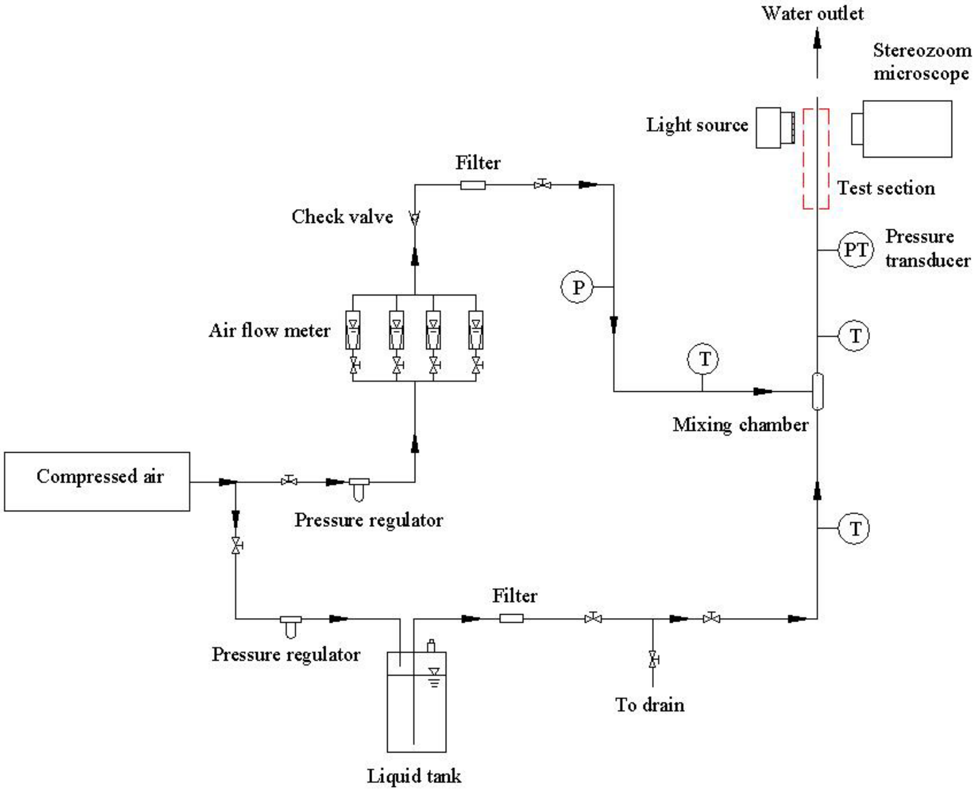

Fig. 1. Schematic diagram of experimental apparatus.

obtained from the viewing window located downstream of the test section as shown in Fig. 2. Descriptions of each flow pattern are defined as shown below.

Slug flow: elongated bubbles which are larger in length than the channel diameter are developed from small bubbles.

Throat-annular flow: the two consecutive elongated bubbles coalesce into a throat-like gas core.

Churn flow: a disruptive region develops due to the distortion of the elongated bubbles.

Annular flow: liquid film flows on the tube wall and the tube core is occupied by continuous vapour flow.

Annular-rivulet flow: annular flow is observed alternately with flowing of a rivulet-like liquid stream on the tube surface.

It should be noted that such peculiar flows as throat-annular flow and annular-rivulet flow have never been observed in ordinarily sized channels even for flow boiling phenomena as reported by Saisorn et al. [12].

The usual method in the presentation of flow pattern data is to classify the flow pattern by visual observation and plot the data as a flow pattern map in terms of system parameters. Parameters used in the present study are the phase superficial velocities.

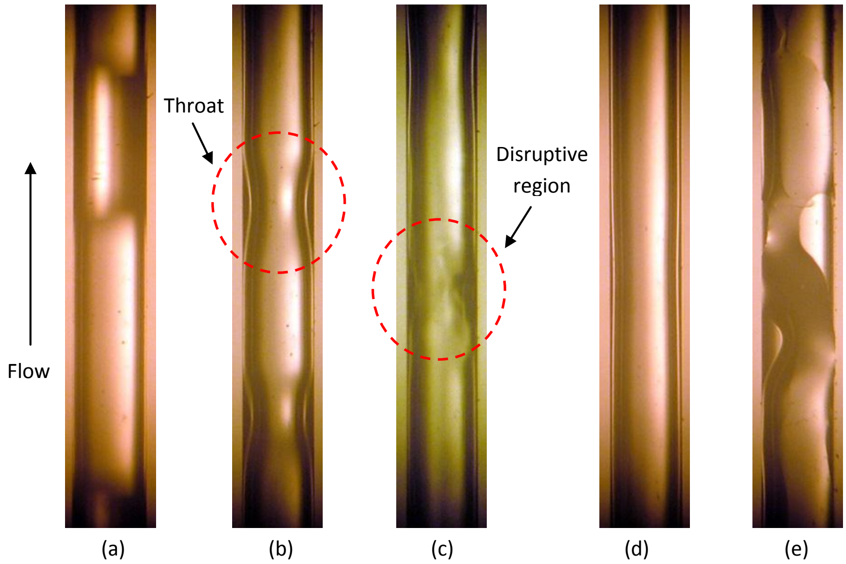

Fig. 2. Flow patterns in a 0.53 mm diameter channel: (a) slug flow at j_L = 0.022 m/s and j_G = 0.380 m/s; (b) throat-annular flow at j_L = 0.021 m/s and j_G = 2.281 m/s; (c) churn flow at j_L = 0.387 m/s and j_G = 8.318 m/s; (d) annular flow at j_L = 0.102 m/s and j_G = 11.937 m/s; (e) annular-rivulet flow at j_L = 0.009

The superficial velocity of gas (j_G) and of liquid (j_L) refer to the situation where the designated phase flows alone in the channel. In the present study, both superficial velocities refer to average ambient conditions (1.013 bar, 30°C). Two-phase flow data and flow pattern map for air-water flow in the vertical micro-channel are illustrated in Fig. 3.

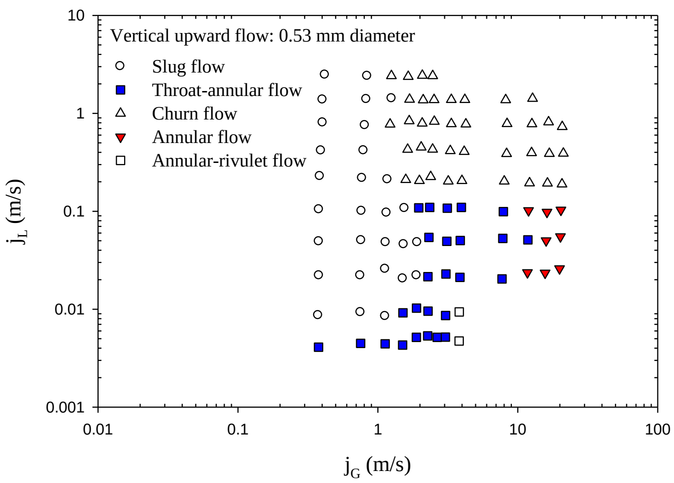

Fig. 3. Flow regime map.

3.2. Two-phase pressure drop

In the present work, the measurements of the total pressure drop of the air-water flow in the 0.53 mm diameter channel are carried out under various different conditions. The total pressure drop of two-phase flow in a vertical channel is expressed by the following balance equation.

$$\Delta P_{exp} = \Delta P_f + \Delta P_a + \Delta P_c + \Delta P_g \quad (1)$$

where ΔP_f is frictional pressure drop, ΔP_a is accelerational pressure drop, ΔP_c represents pressure drop due to sudden contraction and ΔP_g denotes gravitational pressure drop. The latter component can be evaluated by the following expression.

$$\Delta P_g = gL\sin\theta\left[\alpha\rho_G + (1-\alpha)\rho_L\right] \quad (2)$$

The terms pertaining to acceleration and sudden contraction are given in Eqs. (3) – (5).

$$\Delta P_a = G^2\left\{\left[\frac{x^2}{\alpha\rho_G} + \frac{(1-x)^2}{(1-\alpha)\rho_L}\right]_{outlet} - \left[\frac{x^2}{\alpha\rho_G} + \frac{(1-x)^2}{(1-\alpha)\rho_L}\right]_{inlet}\right\} \quad (3)$$

$$\Delta P_c = \frac{G^2}{2\rho_L}\left[\left(\frac{1}{C_c}-1\right)^2 + \left(1-\frac{1}{\gamma^2}\right)\right]\left[1+\left(\frac{\rho_L}{\rho_G}-1\right)x\right] \quad (4)$$

In Eqs.(2) - (4), x represents mass quality, α denotes void fraction which is estimated based on the image analysis, g stands for gravitational acceleration, L is channel length, θ is channel orientation angle, G is mass velocity, ρ_L and ρ_G are liquid and gas densities, respectively. C_c is coefficient of contraction which can be given by Chisholm [13] as shown in Eq.(5).

$$C_c = \frac{1}{0.639\left[1-\left(\frac{1}{\gamma}\right)\right]^{\frac{1}{2}}+1} \quad (5)$$

where γ represents the ratio of the cross-sectional flow area in the flow passage connected to the channel test section to that in the channel test section. The frictional pressure drop can be obtained through the Eqs.(1) – (5). The frictional pressure drop dominates over the other three components as depicted in Fig. 4. Fig. 5 illustrates the frictional pressure drop as a function of superficial gas and liquid velocities. The results reveal that the pressure drop increases with increasing gas or liquid velocity. In addition, churn flow is found to cause pressure drop higher than for the other flow regimes observed during this work.

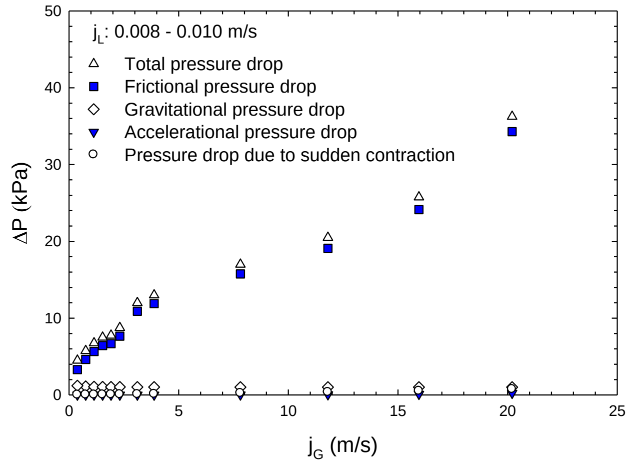

Fig. 4. Pressure drop components for air-water flow in a vertical micro-channel with a diameter of 0.53 mm.

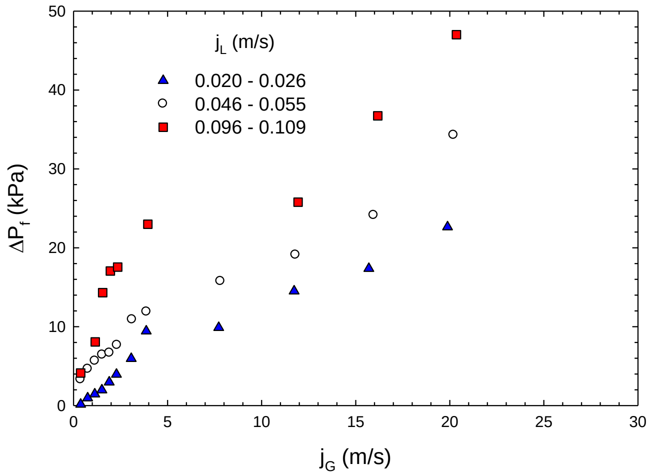

Fig. 5. Frictional pressure drop for air-water flow in a vertical micro-channel with a diameter of 0.53 mm.

4. Conclusion

The experimental investigation is performed to study two-phase flow characteristics in a vertical micro-channel. The test section is a fused silica tube with a diameter of 0.53 mm and a length of 320 mm. Air and water are used as working fluid which is introduced to the test section in vertical upward direction. Based on flow visualization technique employing stereozoom microscope and camera system, slug flow, throat-annular flow, churn flow, annular flow and annular-rivulet flow are observed and used to develop flow regime map in terms of gas superficial velocity and liquid superficial velocity. In addition to flow pattern map, the two-phase pressure drop measurements for vertical upward flow are also carried out in this study. The results indicate the frictional pressure drop larger than the other components including friction, gravitation, fluid acceleration and sudden contraction terms. Increasing gas velocity or liquid velocity can result in the frictional pressure drop increment. It is noted from the results that high pressure drop region takes place in the churn flow regime.

5. Acknowledgements

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