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An experimental study of two-phase air-water flow patterns in rectangular micro-channels

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Abstract

This paper presents a study of air-water two-phase flow patterns during upward flow in vertical rectangular micro-channels. Small size of experimental equipment set was created to be connect with computer will be used in this study. The test section is made from copper plate consisting of 26 parallel rectangular channels. The cross section of each channel is 0.45x0.40 mm^2 and the length is 26 mm. the ranges of gas and liquid superficial velocity are 0.104–4.17 m/s and 0.208–1.46 m/s respectively. Gas and liquid were fed from a common manifold show that in each channel, there was an uneven distribution of air and liquid. All flow characteristics are captured and recorded by a digital camera with high resolution lens. The experimental results show that slug flow and throat-annular flow occur in micro-channel heat sink. Comparison with flow transition boundaries reported in literature are also presented.

Keywords: two-phase air-water flow, rectangular micro-channels, flow pattern.

1. Introduction

Nowadays, the studies on two-phase flow and heat transfer characteristics in micro-channel flow passages have become essential due to the abrupt development of micro-scale devices used for many engineering utilizations including medical devices, high heat-flux compact heat exchangers, and cooling systems equipment such as high performance micro-electronics, supercomputers and high-powered lasers.

Over the past years, single-phase flow of liquid or gas was a major concern and questions about single-phase flow in small channels have been productively resolved. On the other side, the two-phase gas liquid flow in rectangular micro-channels has obtained comparatively little attention in the literature [1].

The classificatory standard of different sized channels has been proposed by several researchers. For example, the confinement number (Co) recommended by Kew and Cornwell [2] is defined as

$$Co = \frac{\sqrt{\dfrac{\sigma}{g(\rho_L - \rho_G)}}}{D_h} \qquad (1)$$

where D_h is hydraulic diameter, σ is surface tension, g is gravitational acceleration, ρ_L and ρ_G are liquid and gas densities. The channel can be classified as ''micro-channel'' if Co is greater than 0.5 Mehendale et al. [3] considered the hydraulic diameter as an important parameter to classify the heat exchangers.

Numerous experimental and theoretical studies have been performed to explore adiabatic gas-liquid two-phase flow in millimeter-sized channels (mini-channels) and micrometer-sized (micro-channels). Two-phase flow patterns, pressure drop and void fraction were inspected for different combinations of channel dimension, working fluids and flow conditions. It was found that as the channel dimension decreased, the stratified flow disappeared and some two-phase flow patterns not characteristic in conventional large channels.

Triplett et al. [5,9] studied the adiabatic two-phase flow characteristics of air-de-ionized water (DI water) in circular 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. Kawaji et al. [6] investigated the effects of channel size and geometry on two-phase flow patterns in the 50, 100, 250 and 530 μm micro channels. The flow patterns in the 250 and 530 μm micro-channels were found to be similar to those in large channels; However, when the channel diameter was reduced to 50 and 100 μm, the bubbly, churn, slug-annular and annular flow patterns were not detected. Only some variations of the slug flow were observed. Cubaud and Ho [7] studied air-water flow in square micro-channels with hydraulic diameters of 200 μm and 525 μm. They concluded that the two-phase flow regime maps were independent of the channel size and the flow regime transition boundaries can be simply determined as a function of the liquid and gas flow rates. Saisorn and Wongwises [4,10] examined two phase flow behaviors during upward flow in of air-water a vertical and horizontal circular micro-channel with diameter 0.53 mm. The flow pattern map was proposed as shown in Fig.1 which includes the slug flow, throat-annular flow, churn flow and annular-rivulet flow. They concluded that the flow patterns observed during vertical upward flow were similar to those found in a horizontal tube with some exceptions.

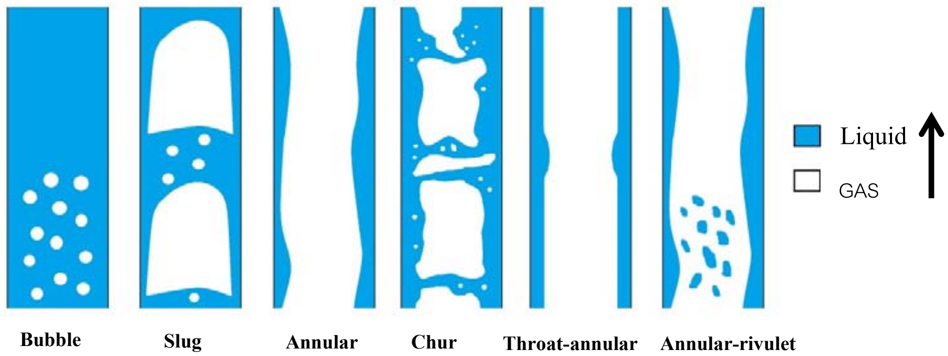


Fig.1 Sketches of the observed flow patterns reported by Saisorn and Wongwises [4,10].

Firstly, the channel orientation can affect the shape of the interfacial surface in the slug flow pattern. The bullet-shaped gas slugs were observed in the horizontal flow. Secondly, with the same flow conditions, the annular flow was observed only in the vertical upward flow channel. Hetsroni et al. [11] Investigated the flow of gas liquid mixture in micro-channel heat sink. The cross-section of each channel was an isosceles triangle. The test module consisted of 21 micro-channels with hydraulic diameter of 130 μm. Gas and liquid were fed from a common manifold. It was observed that different flow patterns, liquid alone (or single-phase flow), bubbly flow, slug flow, and annular flow occurred simultaneously in different channels.

The main objective of the present investigation is to establish a new two-phase rectangular flow pattern in parallel micro-channels having hydraulic diameter of 0.42 mm. It's made from a copper plate consisting of 26 parallel channels. The cross section of each channel is 0.45x0.40 mm^2 and the length is 26 mm. And connected with the small size of experimental equipment that created to be fit in the computer case such as a motor water pump and mini air compressor.

2. Experimental Apparatus

A schematic diagram of the experimental apparatus is shown in Fig. 2. A water pump with adjustable revolutions per minute (rpm) was used to supply liquid flow through the test section. The liquid flow rate is measured using a rotameter ranging between 100-1500 cm^3/min (±5% uncertainty). Mini air compressor is used to generate bubbles. Air flow rate is measured by rotameter within the range of 200-2500 cm^3/min (±5% uncertainty). After water and air has been passed the flow meter and mixed in the T-shaped mixer to introduce fluid smoothly along the test section.

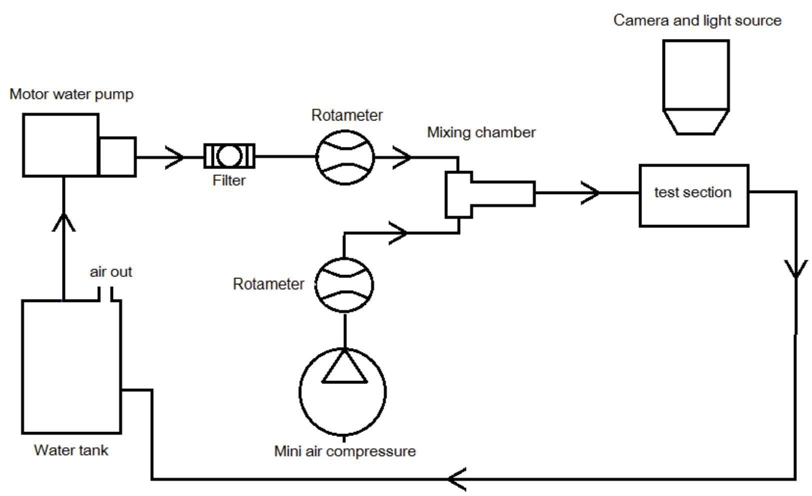
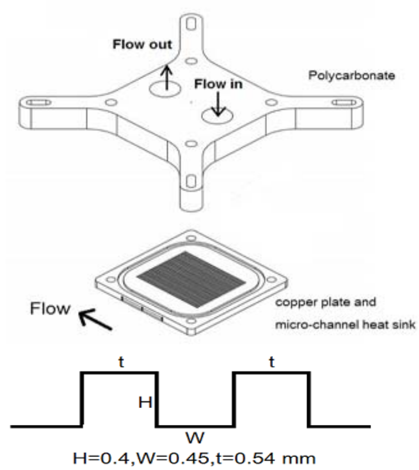


Fig. 2 Schematic diagram of experimental apparatus.

The test section, as shown in Fig.3, is made from a 49x49 mm^2 copper plate, with 3 mm thickness. It consists of 26 parallel rectangular micro-channels of 0.45 x 0.40 mm (width x depth) with a 0.54 mm thick wall between each channel. The length of the micro-channels is 26 mm. On the top of the test section, the cover plate made of polycarbonate is placed to allow optical access for flow visualization.

The detailed formation of flow pattern is recorded using a digital camera with high resolution lens. An LED light source is placed perpendicular to the viewing section.

Experiments are conducted at various combination of air and water flow rates. In the experiments, the air flow rate is increased by a small increment while the water flow rate is kept constant at a pre-selected value. After that, the water flow rate is adjusted to a new value and the procedure is reported. The system is allowed to approach steady conditions before the air and water flow rates as well as the two-phase flow patterns, flow pattern is recorded.



Cross section details of the micro channel

Fig. 3 Schematic diagram of test section.

3. Results and Discussion

3.1 Flow patterns

Due to the fact that the air and water flow rate used in this experiment are comparatively low because of our objective that we wanted to rise slug flow in experimental equipment set that small enough to be connected and used with computer to study heat transfer for CPU in the future.

Only slug and throat-annular flow are observed as shown in Fig.4. Gas and liquid were fed from a common manifold show that in each channel, there was an uneven distribution of air and liquid, it also makes an irregular air and liquid velocity. These are the cause of the differences in size of air bubble among each channel. The main features of the two phase flow patterns are summarized as follows.

3.1.1 Slug flow

Slug flow occurs at a relatively low air velocity and is characterized by elongated bubble flowing in the axial direction. The bubbles become similar in size to the channel height and are separated from the tube wall by the liquid film. With increasing air flow rate, the longer bubbles are observed. Slug flow is also called plug, Taylor, segmented, bubble-train, and intermittent flow

3.1.2 Throat-annular flow

In the region of low liquid flow rates, the formation of The throat-annular flow pattern developing from slug flow pattern is observed at a certain air flow rate. In this pattern, a gas core is surrounded by a liquid film where large-amplitude – waves appear in the liquid film. Throat-annular flow, also known as the Taylor-annular, ring, slug-ring flow, and slug-annular flow.

3.2 Flow regime maps

The usual method in 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. 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 this experiment, rotameter of both air and water were being used to measure the flow ratio before entered the mixing chamber and transferred to test section. The flow pattern map is based on inlet velocity valid in the range of 0.104–4.17 m/s for j_G and 0.208–1.46 m/s for j_L. Superficial velocity define as

$$j_G = \frac{V_G}{A_i},\ j_L = \frac{V_L}{A_i} \qquad (2)$$

Where A_i is the inlet cross-sectional area, and V_G and V_L are the volume flow rates of air and water, respectively

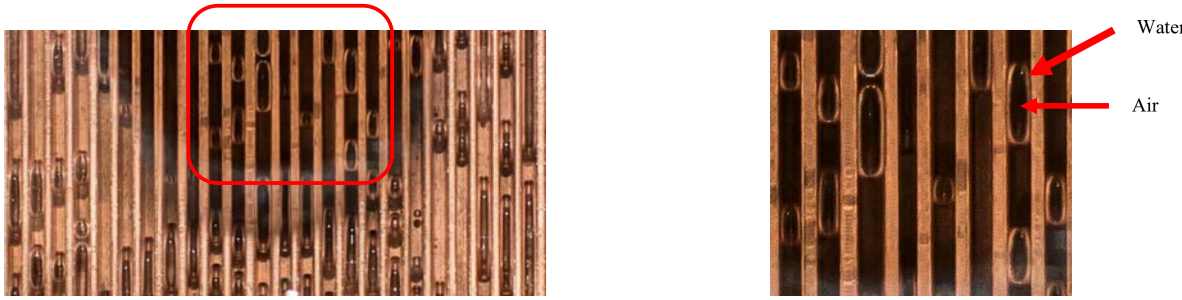
The dash lines in all figures show the range of the flow patterns shift from one flow pattern to another. The comparison between present flow pattern data for the copper test section that consisting of 26 parallel rectangular micro-channel of D_h = 0.42 mm and the flow pattern transitions obtained by

Triplett et al. [5] for two-phase air-DI water flow through a 1.1 mm diameter channel and those obtained by Chung and Kawaji [6] for two-phase flow of nitrogen–DI water in a channel with a diameter of 0.53 mm are presented, in Figs. 5and 6, respectively.

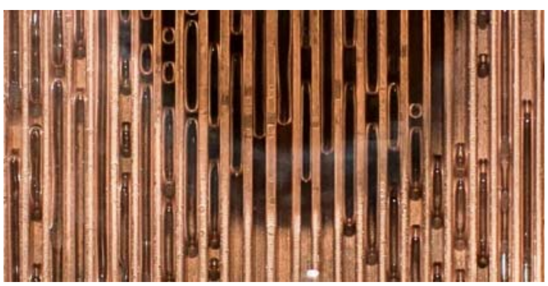
Table 1

Experimental uncertainty.

Parameter	Maximum relative uncertainty
Channel dimensions	±5%
Liquid superficial velocity	±12.8%
Gas superficial velocity	±9.8%

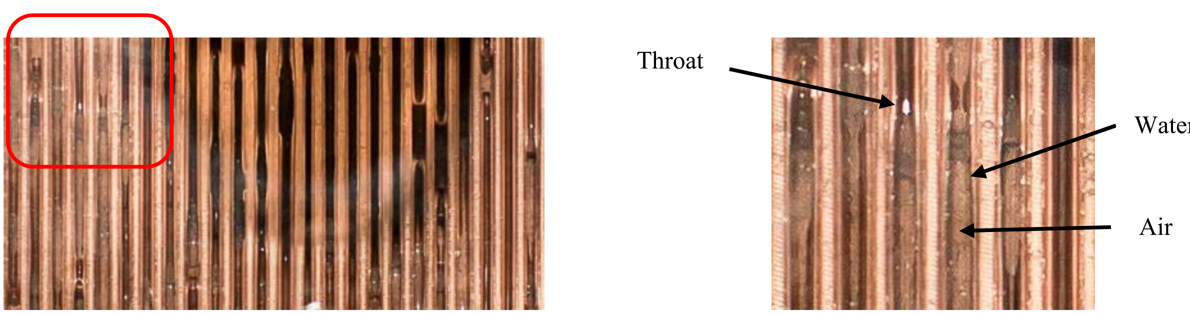


(a) Slug flow with j_G = 0.104 m/s j_L= 0.417 m/s



(b) Slug flow with j_G = 0.625 m/s j_L= 0.417 m/s

(c) Slug flow with j_G = 2.29 m/s j_L= 0.417 m/s



(d) Throat-annular flow with j_G = 3.31 m/s j_L= 0.417 m/s

Fig.4 Flow visualizations of two-phase air–water flow patterns in the present study.

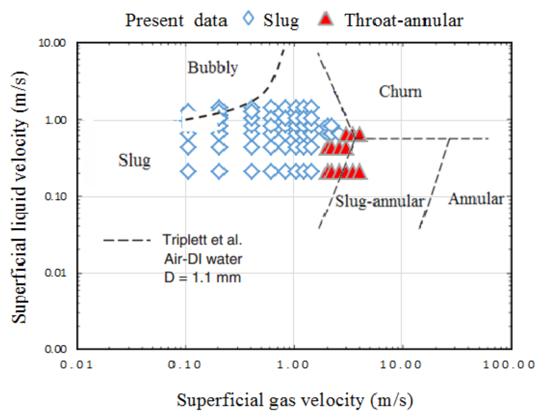


Fig.5 Comparison of observed flow patterns with the transition Lines for Air-DI water, D=1.1mm by Triplett et al. [5]

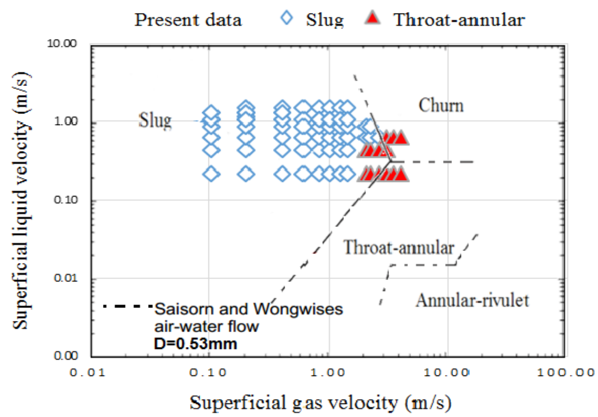


Fig. 7 Comparison of observed flow patterns with the transition Lines for Air-water,D=0.53 mm. by Saisorn and Wongwises [4]

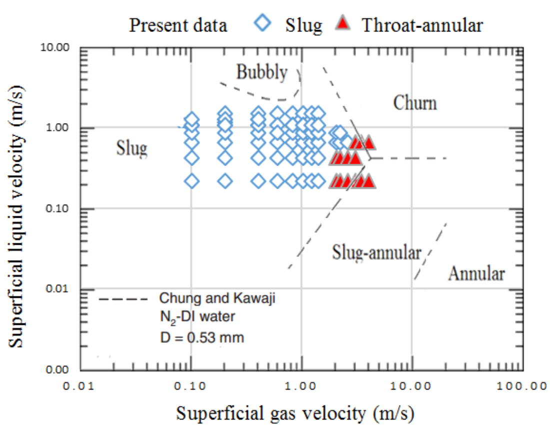


Fig.6 Comparison of observed flow patterns with the transition Lines for N_2-DI water, D=0.53 mm. by Chung and Kawaji [6]

The dash lines along with the flow pattern names indicated on these figures refer to the transition boundaries proposed by the previous researchers. Based on the experimental range of the phase superficial velocities, the result of slug flow from this study agreement with slug flow region and we found some data of throat-annular flow is in the slug flow and slug-annular region proposed by both authors.

Saisorn and Wongwises. [4] carried out two-phase flow experiments using Di-water, water, nitrogen and air as working fluids in a horizontal circular channel with a diameter of 0.53 mm. They reported four major flow patterns including slug flow, throat–annular flow, churn flow and annular-rivulet flow Fig. 7 shows the comparison between present data and their data. We found some part of throat-annular flow is in the slug and throat-annular flow region and slug flow data obtained from the present study well with slug flow region obtained from Saisorn and Wongwises.[4].

4. Conclusion

This study presents a two-phase flow pattern of air-water flow during upward flow in vertical rectangular micro-channel with hydraulic diameter of 0.42 mm. Superficial velocity of gas and liquid are varied from 0.104–4.17 m/s and 0.208–1.46 m/s, respectively. Gas and liquid were fed from a common manifold shows that air and liquid have uneven distribution, in the meantime both air and liquid velocity also unequal, that is the cause of the differences in size of the bubble through each channel. Two flow patterns including slug flow and throat-annular flow are observed. And the boundary of slug flow in parallel micro-channel is harmonized with the study which has similar or bigger size even we used different working fluid, when comparing with a smaller channel the boundary of slug flow is consistent for some part only. And throat-annular's data in parallel micro-channel can be occured in the lower range of gas superficial velocity than the others. The results are in the same trend referred to the study of Xu [8].

And form the experimental process we found that the small set that has been established to be compatible with computer can rise slug flow and we can further develop heat transfer set for CPU in computer.

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