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Original research article

Experimental Study on Two-Phase Flow Pattern of Air-Mixture of Distilled Water and 2% Butanol in Horizontal Mini Channel

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ABSTRACT

Two-phase flow occurs in many modern mini-sized objects. The two-phase flow pattern plays a crucial role in establishing the convection coefficient (h) for both heat transfer and pressure drop ($\triangle$P). The current research examined the two-phase flow pattern in a transparent mini channel with an internal diameter of 1.6 mm. The orientation of the channel was horizontal. The fluids used were air-mixture of distilled water and 2% butanol with the liquid surface tension value of 46.03 mN/m. Superficial velocities of liquid and gas were varied in the range of 0.033 - 4.935 m/s and 0.066 - 66 m/s, respectively. The flow patterns observed were churn, annular, plug-annular, bubbly, and plug. The research also generated a flow pattern map. This map then was compared to those from certain preceding researchers. The findings indicated that the flow pattern map generated in this investigation was only consistent with the one established by Triplett et al. [1] with the exception of the transition boundary from plug flow and bubbly flow to churn flow. The dissimilarity was predicted due to the distinct surface tension of liquid employed. These findings contributed to discover the flow pattern characteristics which are applicable to the cooling performance of microelectronic cooling system, the efficiency of chemical reaction, etc.

Keywords: Experimental study; Flow pattern map; Flow pattern; Mini channel;Two-Phase flow

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1. Introduction

The study of two-phase flow is a narrow field of study, with its result only applicable for certain systems. Due to the narrow field of study, two-phase flow has high complexity.

Two-phase flow may occur in large, normal, mini, micro, and nano channels. The channel size has been divided into six variations by Kandiklar and Grande [2]; conventional channel ($D > 3$ mm), mini channel (3 mm $> D \geq 200$ m), micro channels (200 μm $\geq D > 10$ m), micro-transition channel (10 μm $\geq D > 21$ m), nano-transition channel (1 μm $\geq D >$ 0.1 m), and nanochannels (molecular nano channel) (0.1 μm $\geq D$).

Currently, the fabrication technique for mini-sized objects has been developed and utilized. Along with this, it is necessary to conduct research on the flow in mini channels to optimize the design and safety of the operation of mini products. There are many applications of two-phase flow in the mini channel such as bioengineering applications, microheat pipes, cooling microelectronic circuits, chemical industry, automotive, and aerospace [3–6].

Void fraction, flow pattern, and pressure drop are the essential characteristics of two-phase flow. On the other hand, superficial liquid velocity, superficial gas velocity, liquid surface tension, and liquid viscosity are the main variables affecting the two-phase flow characteristics [7].

Two-phase flow patterns in the mini and micro channel have been studied by many researchers. Some of them are Serizawa et al. [8], Hassan et al. [9], Saisorn et al. [10], Pipathattakul et al. [11], Yin et al. [12], Saisiorn et al. [13], Sudarja et al. [14], Rafalko et al. [15], Zeguai et al. [16], and Shin dan Kim et al. [17]. The important factors that affect flow pattern are surface tension, viscosity, gravitational force, density, flow velocity, and diameter / pipe geometry.

The present study used air-mixture of distilled water and 2% butanol as working fluids. Adding 2% butanol into the distilled water aimed to get the lower surface tension. The value of the surface tension surely affected the flow pattern, which was being the gap of this study. The data collected and analyzed in this study was flow pattern (yielded flow pattern map). One of the purposes on the flow pattern study is to determine the value of convection coefficient (h) on heat transfer and pressure drop (△P). These findings contributed to discover the flow pattern characteristics which is applicable to the cooling performance of microelectronic cooling system, the efficiency of chemical reaction, etc.

2. Governing Equation

The interplay between inertia, viscous shear, surface tension force, and gravity leads to the creation of a two-phase flow pattern [18]. To determine which parameters more significantly affect the flow pattern, the subsequent non-dimensional parameters can be accounted for.

The Reynolds number is defined as the ratio of inertia force to viscous force, and can be written as follows:

$$Re_L = \frac{\rho_L J_L D_C}{\mu_L}, \quad (2.1)$$

$$Re_G = \frac{\rho_G J_G D_C}{\mu_G}. \quad (2.2)$$

The Bond number is defined as the ratio of buoyancy force to surface tension force, and can be written as follows:

$$B_o = \frac{g(\rho_L - \rho_G) D_C^2}{\sigma}, \quad (2.3)$$

The Capillary number is defined as the ratio of viscous force to surface tension force, and can be written as follows:

$$C_a = \frac{\mu_L J_L}{\sigma}, \quad (2.4)$$

The Weber number is defined as the ratio of inertia force to surface tension force, and can be written as follows:

$$We_L = \frac{\rho_L J_L^2 D_C}{\sigma}, \quad (2.5)$$

$$We_G = \frac{\rho_G J_G^2 D_C}{\sigma}, \quad (2.6)$$

where ρ represents density, J represents superficial velocity, D_c represents the internal diameter of the channel, μ represents viscosity, σ represents surface tension, L and G subscript represent liquid and gas phases, respectively.

3. Experimental Setup

The components of the experimental setup of the present study were water tank, water pump, pressure tank, liquid flowmeter, mixer, test section, watertrap, compressor, camera, valydine pressure transducer, acquisition system and computer, copal pressure transducer, and air flowmeter. In general, the experimental scheme of this study is shown in Fig. 1. The pipe employed had the inner diameter of 1.6 mm and was made of glass, in horizontal position.

A mixture of distilled water and butanol from tank (A) was pumped by water pump (B) to enter the pressure vessel (C). A pressure vessel served to keep the flow and liquid temperature more stable than the direct use of the pump. After the mixture of distilled water and butanol reached maximum volume in the pressure vessel, air was used to push the liquid mixture out of the

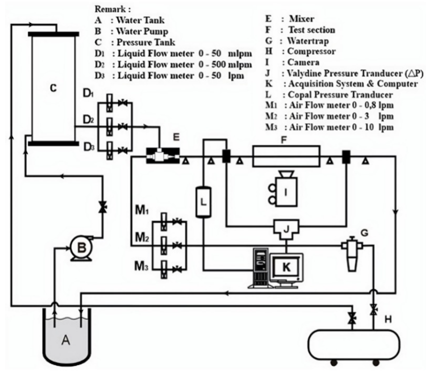

Fig. 1. Experimental scheme.

pressure vessel to the liquid flowmeter (D). Meanwhile, air was delivered by using the compressor (H) through the watertrap (G) to the air flowmeter (M). In the flowmeter, the discharge of air-mixture of distilled water and butanol were set to get certain JG and JL. Simultaneously air-mixture of distilled water and butanol flowed out of the flowmeter to the mixer (E). In the mixer, air-distilled water and butanol were mixed and drained through the pipe and passed the test section (F) to be photographed. The photographs were captured to obtain flow pattern data. Furthermore, the air-mixture of distilled water and butanol came out of the pipeline passing through the separator to separate the both.

The fluids utilized in the current investigation were air, distilled water, and butanol. Butanol mixed with distilled water with the percentage of 2% of butanol. At 25°C and ambient pressure (1 atm), the mixture of distilled water and 2% butanol has the surface tension (σ) of 0.046 N/m and density (ρ) of 994 kg/m^3.

4. Results and Discussions

The non-dimensional parameters for two-phase flow in the channel with diameter of 1.6 mm are shown in Table

1. The parameters were obtained using Eqs. (2.1)-(2.4). The properties used in the calculations were: ρL =994 kg/m^3, ρG =1.2 kg/m3, μL =8.386×10^{-4} Ns/m^2, μG =1.8×10^{-5} Ns/m^2, and σ =0.046 N/m. It can be concluded that in the channel with the internal diameter of 1.6 mm, inertia and surface tension force are relatively more important than buoyancy and viscous force (B_o <<1, C_a <<1). Thus, the effect of buoyancy and viscous force can be neglected.

Table 1. Dimensionless parameters for two-phase flow in the channel with inner diameter of 1.6 mm.

Re_L	Min	62.58431
	Max	9359.199
Re_G	Min	7.04
	Max	7040
B_o		0.541464
C_a	Min	0.000602
	Max	0.089967
We_L	Min	0.037651
	Max	842.0209
We_G	Min	0.000182
	Max	181.8157

4.1 Flow patterns and flow pattern map

The flow patterns observed in the current study were churn, annular, plug-annular, bubbly, and plug. Representative photographs of those flow patterns are depicted in Figs. 2-6, respectively. Stratified flow did not occur in the present study (generally in the mini channel) due to the suppression of buoyancy effect by surface tension force.

Plug is a flow pattern where gas phase and liquid phase flow intermittently in the pipe. Some other researchers named it plug [19], elongated bubble [1], and bubble-train [20]. As shown in the flow pattern map (Fig. 6), plug flow established at low-moderate J_G (0.066-0.871 m/s) and J_L (0.033-0.539 m/s). As the superficial gas velocity increased, plug flow was getting longer. The second pattern observed was bubbly, which occurred when J_L was increased. Bubbly flow is dominated by liquid phase. The curvature of the bubbly was affected by gravity. It is not discussed since the ratio of gravitational force to surface tension is small, thus the effect can be neglected [18]. Bubbly flow occurred at low J_G (0.066-0.207 m/s) and moderate-high J_L (0.879-1.493 m/s). The next pattern observed was plug-annular, which is the transition pattern from plug to annular. Plug-annular has a liquid neck which is established after the interfacial instability waves arising from the viscous shear stress [18]. This pattern occurred at moderate J_G (1.941-22.26 m/s) and low-moderate J_L (0.033-0.232 m/s). The fourth pattern was annular flow where inertia force completely dominated [18]. In annular flow pattern, gas phase flows between liquid films. It occurred at high J_G (36.964-66 m/s) and low-moderate J_L (0.033-0.232 m/s). The last pattern observed was churn flow, which occurred at low-high J_G (0.066-66 m/s) and J_L (0.149-4.935 m/s). Churn flow was assumed to be established after bubbly or plug flow became unstable at their tail.

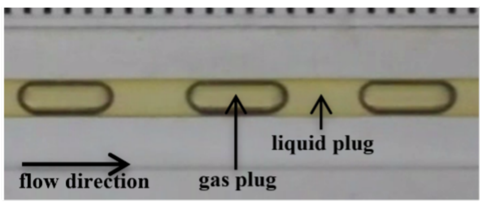

Fig. 2. Plug flow (J_G = 0.066 m/s, J_L = 0.033 m/s).

As noted earlier, the flow pattern map obtained in the current investigation is represented by Fig. 7. The X-axis represents superficial gas velocity (J_G) while the

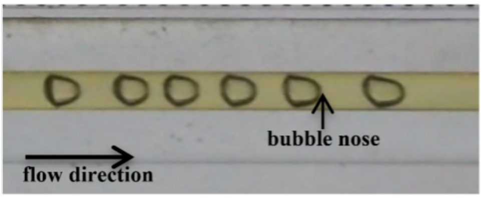

Fig. 3. Bubbly flow (J_G = 0.207 m/s, J_L = 0.879 m/s).

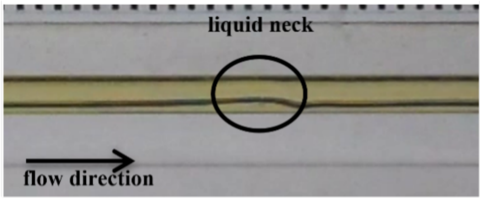

Fig. 4. Plug-annular flow (J_G = 1.941 m/s, J_L = 0.033 m/s).

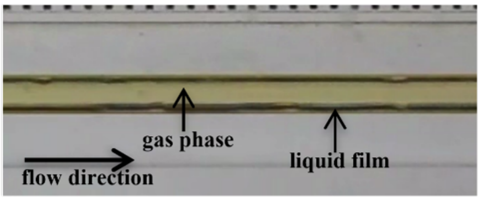

Fig. 5. Annular flow (J_G = 36.964 m/s, J_L = 0.091 m/s).

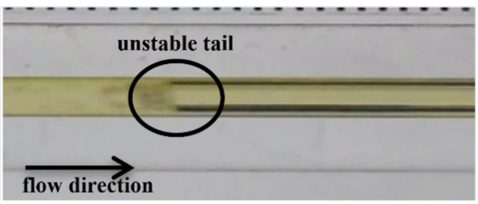

Fig. 6. Churn flow (J_G = 0.207 m/s, J_L = 2.297 m/s).

Y-axis represents superficial liquid velocity (J_L). The lines on the map represent the transition boundary. As can be seen, churn flow dominates the area of the map. The map was then compared to those from some previous researchers. Further discussion about the comparisons will be presented in the next sub-section.

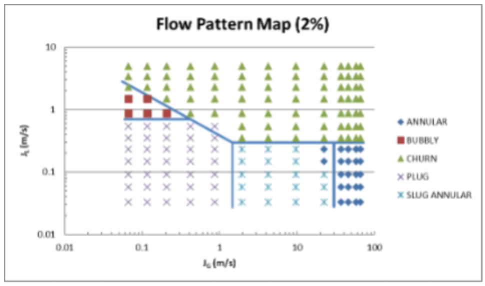

Fig. 7. Flow pattern map.

4.2 Flow pattern map comparisons

The flow pattern map obtained in the current investigation then was compared to those from some previous researchers. The first researcher was Triplett et al. [1] which executed a laboratory examination on the behavior of a two-phase flow of air-water combination inside a circular mini channel in horizontal orientation having inner diameter of 1.45 mm. The second was research by Sadatomi et al. [21]. They conducted experimental investigation on the two-phase flow of air-water mixture in circular horizontal mini channel with the inner diameter of 3 mm. The next comparison was to a map by Chung and Kawaji [22] which studied two-phase nitrogen-water flow in circular horizontal mini channel having inner diameter of 0.53 mm. The map was also compared to that by Hua and Pu [23] which studied a two-phase nitrogen-mixture of water and SDBs flow pattern in horizontal tube with the internal dimension of 1.6 mm. The channel utilized by the four researchers can be categorized into mini channel [2].

As shown in Fig. 8, flow patterns observed in the current study were similar to that by Triplett et al. [1]. The map is also similar, except for the transition of bubbly and plug to churn. The difference was predicted caused by the different surface tension of liquid employed. As the surface tension decreases, cohesion forces among the liquid molecules are smaller. It was assumed to lead to the instability of the bubbly or plug flow, so that they turned into churn flow.

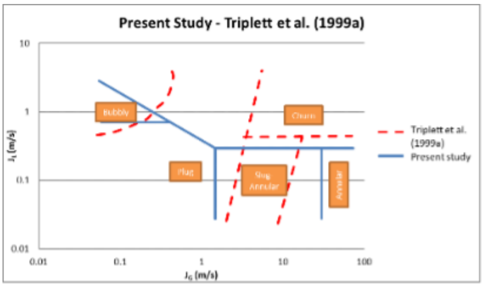

Fig. 8. Flow pattern map comparison of the current study and by Triplett et al. [1].

The next comparison was to a map by Sadatomi et al. [21]. The result is shown in Fig. 9 and it can be seen that the observed flow pattern between the two researchers is not similar. Sadatomi et al. [21] only observed 3 flow patterns, namely bubbly, plug, and annular. The transition line was also significantly different. The difference was predicted to be caused by two reasons:; the different properties of gas and liquid employed, and the different range of J_L (Sadatomi et al. only varied J_L of 0.1 < J_L < 2 m/s).

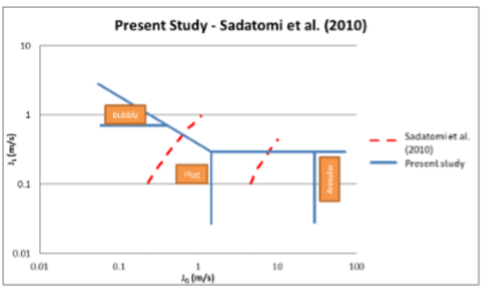

Fig. 9. Flow pattern map comparison of the current study and by Sadatomi et al. [21].

Fig. 10 represents the flow pattern map comparison between the current study and that by Chung and Kawaji [22]. Chung and Kawaji studied the nitrogen gas-water flow characteristics and observed the similar flow pattern also, but the comparison shows sufficiently different transition line between the two researchers. The difference was predicted to be caused by the different properties of the fluids employed. The surface tension of the present study was higher than Chung and Kawaji. The lower surface tension was also assumed to lead the instability of the bubbly or plug flow, so as they turned into churn flow at lower J_L.

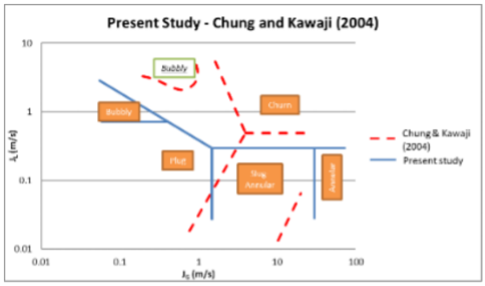

Fig. 10. Flow pattern map comparison of the current study and by Chung and Kawaji [22].

Fig. 11 shows the significantly different flow pattern transitions between the two researchers. The dissimilarity was predicted due to the distinct surface tension of liquid employed. On the other side, the flow patterns observed did not agree well either. Hua and Pu [23] observed only 4 flow patterns, namely bubbly, plug, plug, and annular. Churn flow and plug-annular flow did not establish in their study.

5. Conclusion

Two-phase flow pattern inside a circular mini channel (with horizontal orientation) using air-mixture of distilled water and 2% butanol have been investigated in this paper. The main conclusions which can be drawn from this study are as follows:

1) The flow patterns obtained in the current study were churn, annular, plug-

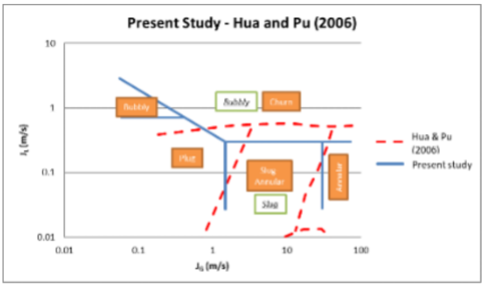

Fig. 11. Flow pattern map comparison of the current study and by Hua and Pu [23].

annular, bubbly, and plug. The flow pattern affected the cooling performance of microelectronic cooling system and the efficiency of chemical reaction.

2) Stratified flow did not occur in the present study (generally in mini channel) due to the suppression of buoyancy effect by surface tension force.

3) Comparison to the flow pattern maps of some previous researchers showed that mostly, the present map only agreed well with that by Triplett et al. [1] except for the transition of bubbly and plug to churn. The difference was predicted to be caused by the different surface tension of liquid employed.

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