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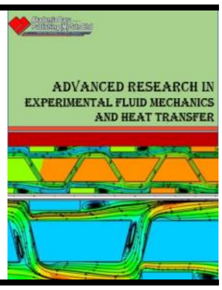

Experimental Study on Flow Pattern and Void Fraction of Air-Water and 3 % Butanol Two-Phase Flow in 30^o Inclined Mini Channel

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ABSTRACT

The study on flow pattern and void fraction of air-water and 3 % butanol two-phase flow in 30^o inclined mini channel was performed experimentally. The aim of the research was to find-out the two-phase flow characteristics of gas and low surface tension liquid, especially flow regime and void fraction. A 1.6 mm inner diameter and 130 mm length circular glass pipe was used as test section. The flow images were found by capturing the flow with high speed camera. From the video, it was obtained the flow patterns and flow pattern map. Besides, the flow void fraction which obtained by image processing. The gas and liquid superficial velocities were set in the range of 0.025 - 66.3 m/s, and 0.033 - 4.935 m/s, respectively. Dry air is used as gas working fluid, while as liquid one was the solution of distilled water and 3% Butanol. The addition of Butanol to the liquid phase was intended to change the liquid surface tension. As a result, it was observed five distinctive flow patterns, namely plug, slug-annular, churn, bubbly, and annular. The separated flow was absent. The change of the liquid surface tension affected to the shifting of some transition boundary line in the flow pattern map. Besides, it influenced to the characteristic of void fraction.

Keywords:
Gas-liquid two-phase flow; mini channel; surface tension; flow pattern; void fraction

1. Introduction

As stated by Kawahara *et al.,* [1], the application of two-phase flow in the mini pipe is very wide fields, such as in in microelectronic circuits, aerospace and micro heat pipes, and bioengineering applications. Other applications are in the field of the cooling of high-density multi-chip modules in supercomputers, high-flux heat exchangers in aerospace systems, cryogenic cooling systems in satellites, and high-powered X-ray and other diagnostic devices [2].

Some authors reported the results of their research on the two-phase flow in small size channel among others Tsaoulidis *et al.,* [3], Hassan *et al.,* [4], Lee and Lee [5], Saidi *et al.,* [6], Chung and Kawaji [7], and Zhao *et al.,* [8], Sudarja *et al.,* [9-10].

Flow pattern, void fraction, and pressure gradient are the basic characteristic in two-phase flow. The main variables which contribute to affect the two-phase flow characteristic are gas superficial velocity, liquid superficial velocity, liquid viscosity, and liquid surface tension. Some authors who

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investigated the effects of liquid viscosity among others Fukano and Furukawa [11], Furukawa and Fukano [12], Sowinski and Dziubinski [13], Matsubara and Naito [14], Mc Neil and Stuart [15], Zhao *et al.,* [16], Sudarja *et al.,* [17], and Sukamta [18-19], while the effect of liquid surface tension to two-phase flow parameters were studied by Krishnamurthy and Peles [20], and Sadatomi *et al.,* [21].

Krishnamurthy and Peles [20] reported their studies on two-phase flow across a bank of 100 μm diameter staggered circular micro pillars, 100 μm long with pitch-to-diameter ratio of 1.5. They used ethanol for liquid working fluid, and the Reynolds number between 5 and 50. The experimental results were compared to those of using water. From the flow pattern map, it was shown that the flow regimes were similar for two liquid. However, there was some discrepancies in the transition lines. There is no significant effect of surface tension to the void fraction, while it significantly affected to the pressure drop characteristics.

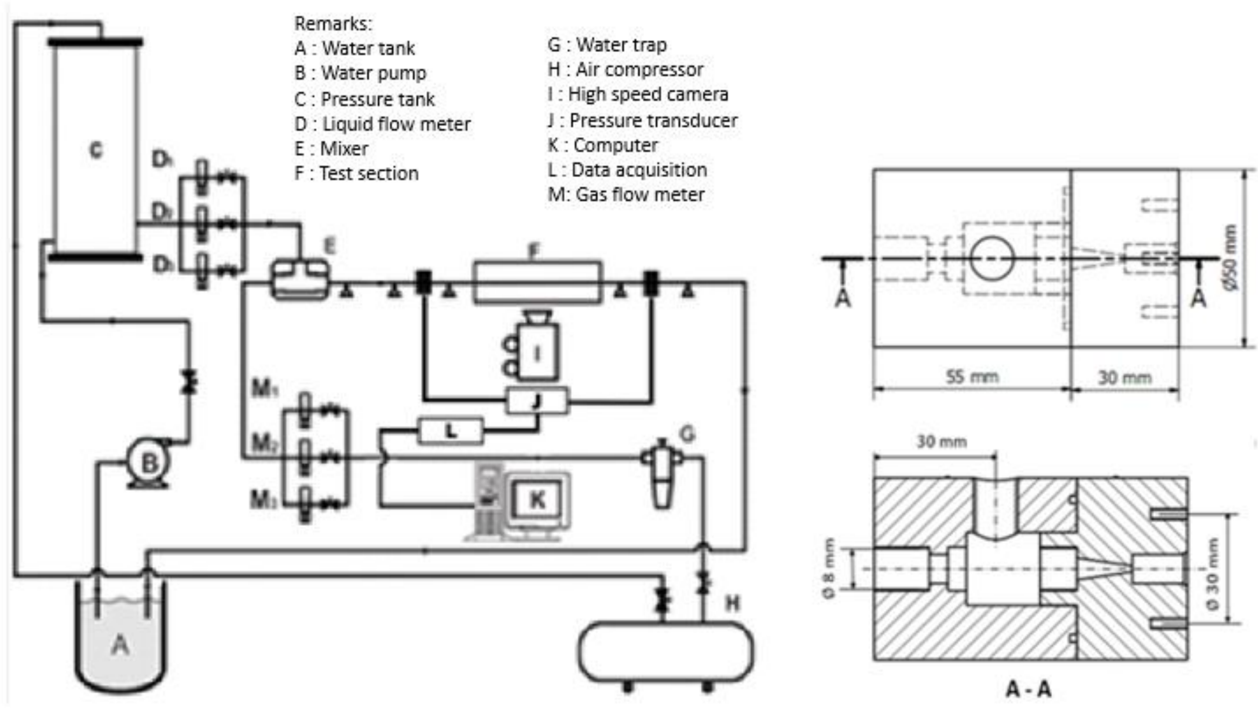
Sadatomi *et al.,* [21] conducted the experimental studies on the effects of pipe diameter and liquid surface tension to the flow characteristics. They used 3,5, and 9 mm inner diameter, and employed 4 kinds of liquids with different surface tension. From the experiment results, they concluded that the pipe diameter and liquid surface tension affects strongly to the transition line and the liquid surface tension did not affect significantly to the frictional pressure drop but strongly affected to the interfacial friction force and void fraction.

The above explanation shows that no researcher has carried-out the experiment and discussed about the effect of liquid surface tension to the characteristics of two-phase flow in mini or micro channel in an inclined orientation. Therefore, study on the effect of liquid surface tension on the gas-liquid two-phase flow pattern in 30^o inclined capillary pipe was very important to be carried-out experimentally.

2. Methodology

Gas and liquid were employed as working fluids in the present study. Dry air was used as gas fluid, while mixture solution of distilled water and 3% Butanol as liquid fluid. The addition of Butanol aimed to reduce the liquid surface tension. The surface tension of water was 71 mili Newton/meter (mN/m), while that of Butanol was 24.37 mN/m, and the that of mixture solution of water and 3% Butanol was 42.9 mN/m. The experimental rig used in the present study is shown schematically in Figure 1, as also previously used, and reported by Sudarja *et al.,* [9-10, 17]. A 1.6 mm inner diameter glass pipe with length of 130 mm was employed as test section. The experimental apparatus was also equipped with optical correction box, mixer, liquid flow meter, gas flow meter, camera, pressure transducer, data acquisition, and computer. The optical correction box was aimed to eliminate pipe surface curve effect. Perpendicular entrance type mixer was used to mix both gas and liquid phase working fluid prior to test section.

Liquid flow meter used in the study are form Omega and TOKYO KEISO, with accuracy of $\pm$ 5 % and $\pm$ 3 %, respectively. For capturing the flow images, Nikon J4 high-speed video camera with speed of 1200 fps and resolution of 640 x 480 pixel was employed. Pressure transducer from Dwyer which coupled with Advantech data acquisition were used to measure the pressure drop along test section. Ranges of gas and liquid superficial velocity were 0,025 – 66,3 m/s, and 0,033 – 4,935 m/s, respectively. The experiment was conducted in adiabatic condition. The flow patterns were obtained from the video images of the flow, while the void fraction was obtained from the result of image processing.



(a) (b)

Fig. 1. (a) Schematic diagram of experimental apparatus, (b) mixer

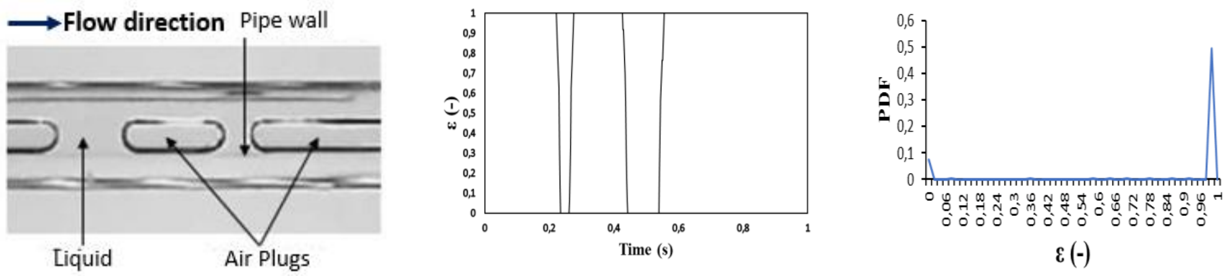
3. Results

3.1 Flow Pattern and Void Fraction

Plug, bubbly, slug-annular, annular, and churn flow patterns occurred in the present study, meanwhile, the separated flow (or sometimes called stratified flow) was not observed. It was indicated that the surface tension effect was more dominant than the gravitation. The explanation of each flow regime and its void fraction is given below.

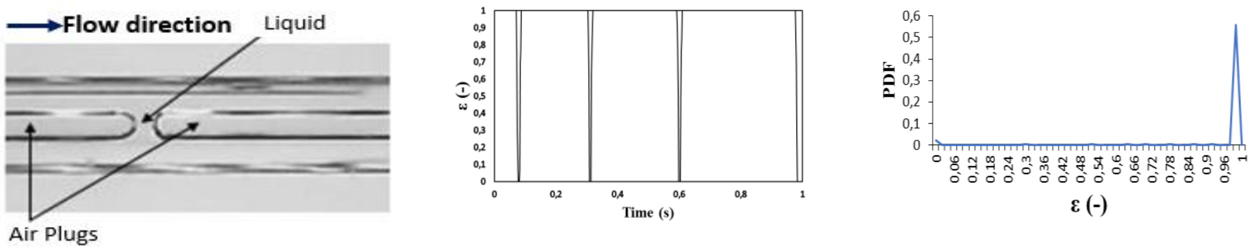
3.1.1 Plug flow

The characteristics of plug flow, in term of flow pattern and void fraction, are shown in Figures 2 and 3. Plug flow is characterized by the intermittent flow of gas plug and water bridge. Plug flow is occurred at low of both J_G and J_L, and at moderate J_G with low to moderate J_L. This condition is in line with those reported by Sudarja *et al.,* [10]. From Figure 2 and Figure 3, it is seen that superficial velocity of gas (J_G) affects strongly to the plug length, here, the higher the J_G the longer the gas plug. This condition also stated previously by Fukano and Kariyasaki [22], Saisorn and Wongwises [23], and Sudarja *et al.,* [10]. From the void fraction time series, it is clearly appeared that plug diameter is same as the inner diameter of pipe, which indicated by the magnitude of void fraction is equal to 1. This is also confirmed with the PDF which is dominant in the value of 1 and 0. 0 means water bridge flow, 1 is the body of plug. The void fraction values between 0 and 1 are the nose and tail of the plug.



(a) Flow pattern (b) Void fraction time series (c) PDF

Fig. 2. Plug flow at J_G = 0.066 m/s and J_L = 0.149 m/s for B3, 30° inclined orientation

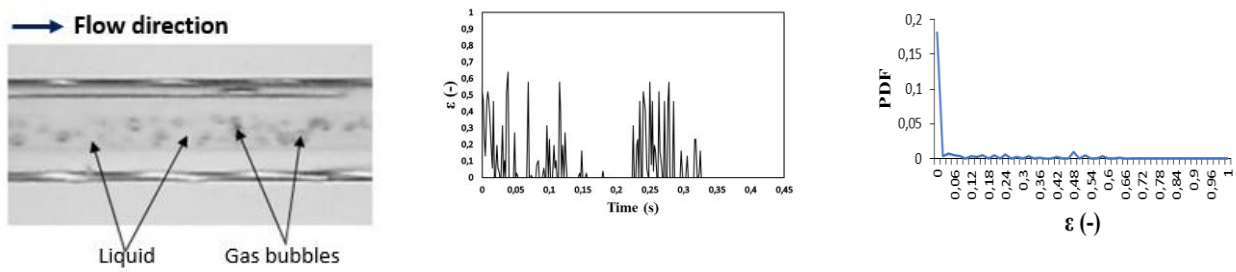


(a) Flow pattern (b) Void fraction time series (c) PDF

Fig. 3. Plug flow at J_G = 0.207 m/s and J_L = 0.149 m/s for B3, 30° inclined orientation

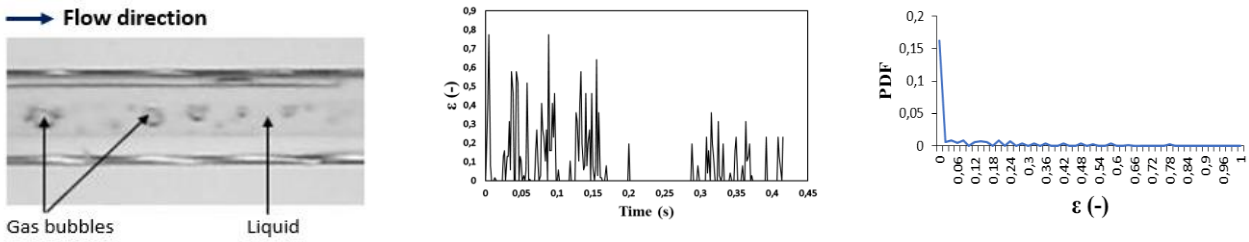
3.1.2 Bubbly flow

Bubbly flow pattern is occurred at very low J_G and high J_L. The bubbly flow in the present experiment is not a single flow, but a mixed flow, because sometimes a long plug appears and followed by dispersed bubbles. Flow pattern and void fraction of bubbly flow are depicted in Figure 4 and Figure 5, which consist of flow image, time series of void fraction, and PDF of void fraction. From the void fraction time series graph, it is seen that the magnitude of the void fraction is low, which can be interpreted that there is no bubble with diameter same as the channel diameter. The void fraction PDF shows that its value is dominant in the value of 0. It means that the liquid flow is dominant. When J_G is raised (0.066 m/s to 0.116 m/s) the bubble size become bigger and less water domination (0.18 to 0.16)



(a) Flow pattern (b) Void fraction time series (c) PDF

Fig. 4. Bubbly flow at J_G = 0.066 m/s and J_L = 2.297 m/s for B3, 30° inclined orientation

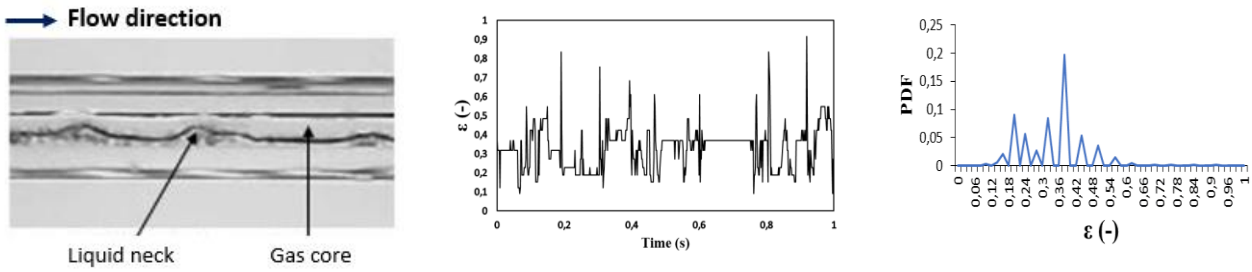


(a) Flow pattern (b) Void fraction time series (c) PDF

Fig. 5. Bubbly flow at J_G = 0.116 m/s and J_L = 2.297 m/s for B3, 30° inclined orientation

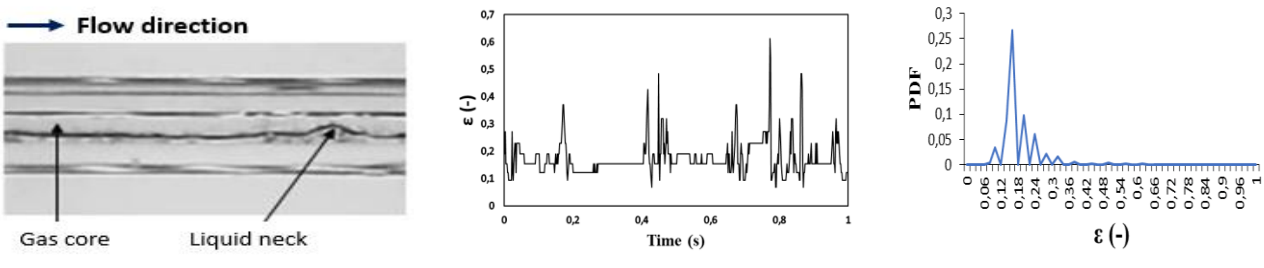
3.1.3 Slug-annular flow

At high J_G and low J_L, the flow pattern is slug annular. Slug-annular flow is formed from plug flow when the J_G is increased. At certain J_G, gas pushes and pierces liquid bridge. The gas forms gas core flow in the center of the channel, while the liquid forms liquid film flow at the pipe wall. In some point, the liquid films are thicker than the other points and form liquid neck. Hence, the characteristic of slug-annular flow is the appearance of liquid necks. Figure 6 and Figure 7 show clearly the effect increasing J_L. In the void fraction time series graph, it is shown that the void fraction is lower when J_L is increased. It can be also confirmed form the PDF, that the peak frequency is shifted to the lower void fraction, when the J_L is increased.



(a) Flow pattern (b) Void fraction time series (c) PDF

Fig. 6. Slug-annular flow at J_G = 3 m/s and J_L = 0.0091 m/s for B3, 30° inclined orientation

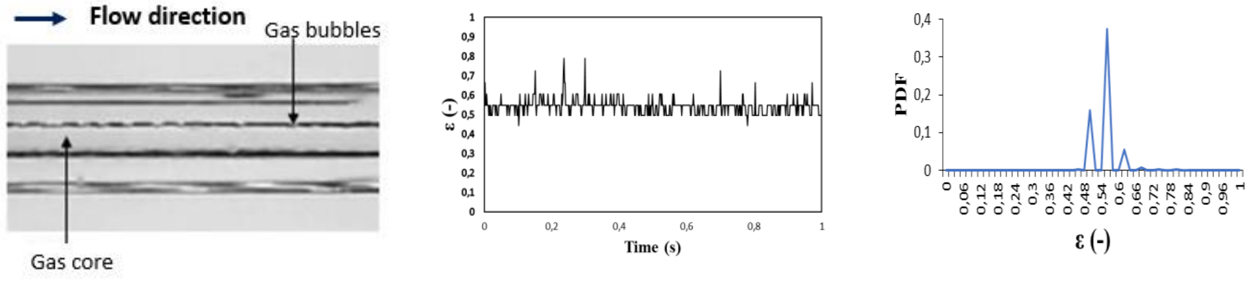


(a) Flow pattern (b) Void fraction time series (c) PDF

Fig. 7. Slug-annular flow at J_G = 3 m/s and J_L = 0.033 m/s for B3, 30° inclined orientation

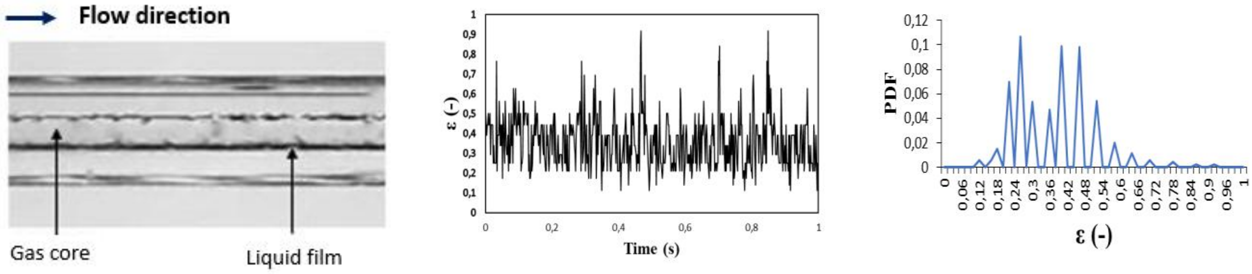
3.1.4 Annular flow

Annular flow or sometimes called it ring flow, occurred at high J_G and low J_L. As shown in Figure 8 and Figure 9, annular flow consists of gas core and liquid film. From the flow pattern configuration, it can be seen that the increase of J_L caused the thicker liquid film, conversely, the higher J_G, the liquid film tends to thinner. The increasing J_L also caused higher ripples at the flow interface. Meanwhile, from the void fraction time series graph and the PDF, it seems that increasing J_L caused lower void fraction and spread in wider range. It indicates that the void fraction is in higher fluctuation at higher J_L.



(a) Flow pattern (b) Void fraction time series (c) PDF

Fig. 8. Annular flow at J_G = 50 m/s and J_L = 0.033 m/s for B3, 30° inclined orientation

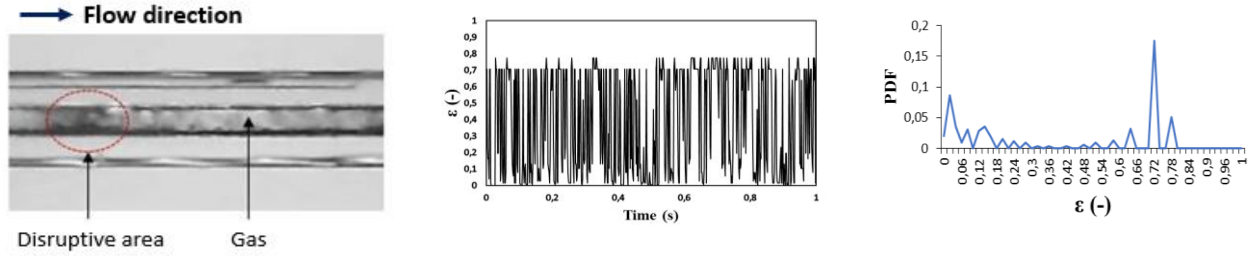


(a) Flow pattern (b) Void fraction time series (c) PDF

Fig. 9. Annular flow at J_G = 50 m/s and J_L = 0.091 m/s for B3, 30° inclined orientation

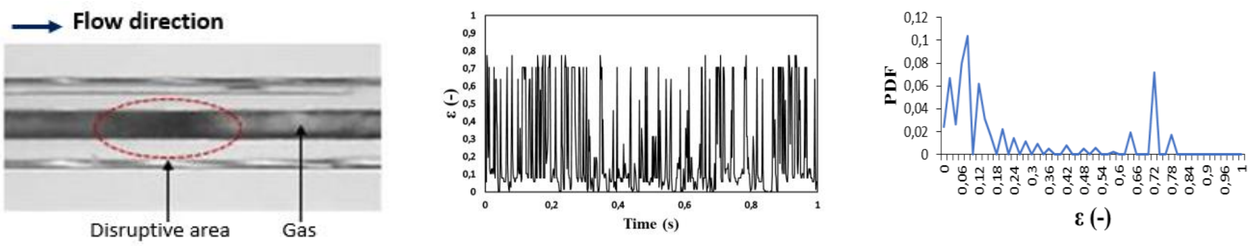
3.1.5 Churn flow

Churn flow is obtained at high of both J_G and J_L. Some disruptive regions are appeared as depicted in Figure 10 and Figure 11. It caused by the turbulence and mixture flow of liquid and gas. As shown in those figures, higher J_L implies more disruptive area and darker appeared. In term of void fraction, increasing of J_L tends to lower void fraction. From the PDF, it is seen that the peak of the frequency shifts to left side, or in the other words, it shifts to the lower value of void fraction.



(a) Flow pattern (b) Void fraction time series (c) PDF

Fig. 10. Churn flow at J_G = 22.6 m/s and J_L = 0.539 m/s for B3, 30° inclined orientation



(a) Flow pattern (b) Void fraction time series (c) PDF

Fig. 11. Churn flow at J_G = 22.6 m/s and J_L = 0.7 m/s for B3, 30° inclined orientation

3.2 Flow Pattern Map

The flow pattern map is plotted in horizontal and vertical axes which are superficial velocities gas and liquid, respectively. Both axes are stated in logarithmic scale. It is intended to cover the wide range of both J_G and J_L. The ranges of J_G and J_L are 0.025 – 66.3 m/s and 0.033 – 4.935 m/s, respectively. The flow pattern map of the present study is shown in Figure 12. It seen that the plug and churn flow regimes occupy the widest area.

The map is also compared to the other experimental results proposed by previous researchers, Triplett *et al.,* [24] and Chung and Kawaji [7], which using water (higher surface tension] as liquid working fluid as shown in Figure 13. In term of type of flow patterns observed, it can be said that all are in a good agreement. However, as for the transition line, there are some differences. The transition line between slug-annular and annular against churn flow is shifted to lower side or toward lower J_L when the liquid surface tension is decreased. It means that the churn flow area is wider or in the other words, the churn flow is easier formed when the liquid surface tension is lower. This condition is the implication of the high turbulence of both fluids.

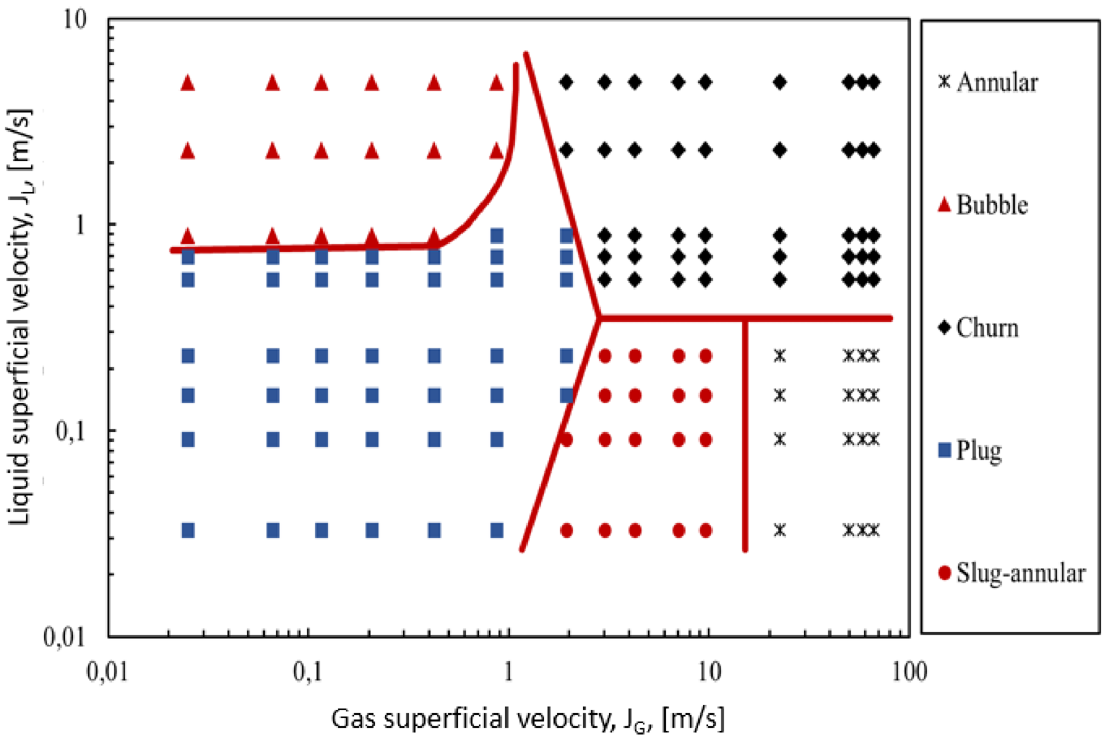


Fig. 12. Flow pattern map of B3 gas-liquid two-phase flow

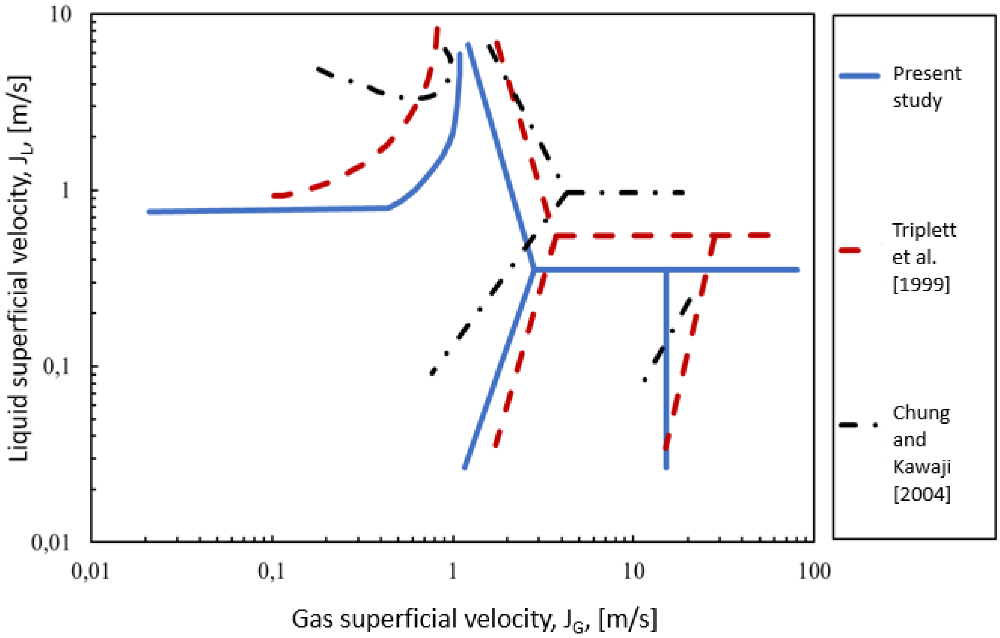


Fig. 13. Flow pattern map comparison present against the previous study

4. Conclusions

The experimental research on the gas-liquid two-phase flow pattern and void fraction in mini channel using low surface tension liquid in adiabatic condition was done. The ranges of gas and liquid superficial velocities were 0.025-66.3 m/s and 0.033-4.935 m/s, respectively. The liquid was solution of water and Butanol with the percentage of 3%, while the gas phase was dry air. From the results and discussion, it can be summarized as follows:

I. Annular, bubbly, churn, plug, and slug-annular flow patterns occurred in the present study, meanwhile, the separated flow was not observed.
II. The bubbly flow observed in present study is dispersed bubbly.
III. Both gas and liquid superficial velocities influence the flow configuration of the flow and its void fraction.
IV. The transition line between slug-annular and annular against churn flow is shifted to lower side or toward lower J_L when the liquid surface tension is decreased. It means that the churn flow is easier formed when the liquid surface tension is lower.

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