Visualization Study of Air-Water Two-Phase Flow Pattern in Upward Vertical Flow of Square Channel

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Abstract. An important two-phase flow experiment study is carried out as a consideration in the application of piping system design that depends on two-phase flow. The purpose of this study was to determine the air-water flow pattern formed in a small square channel with vertical flow direction and to know the flow configuration. Channel 5 mm hydraulic diameter was used in this study. Bubble, slug, churn, and annular flow patterns are formed in the air superficial velocity range 0.33 - 7.31 m/s and superficial velocity of water is 0.13 - 1.2 m/s. A flow pattern map produced has not similarities with the mini-channel flow pattern map in previous studies. The velocity of bubbles and void fractions increases with the increase of superficial air velocity. The void fraction of present research has a good correlation to the results of predictions proposed by previous studies.

Keywords: two-phase flow, flow configuration, vertical flow

1. Introduction
The engineering processes involve more than one phase of the compound, and some processes require phase changes to process materials or to transfer energy, such as oil refineries, chemical and food processes, and energy generation. Since the 1940s, engineers and scientists have been aware of the significant influence caused by the existence of two-phase fluid in a system. Two-phase flow is part of a multi-phase flow involving two of the three phases (solid, liquid and gas) that flow together in a flow system. Two-phase flow is more complex than single-phase flow because the flow characteristics are not only affected by pressure drop but also flow patterns [1]. To design and operate an optimal two-phase flow system, the design engineer must predict the flow pattern that will occur accurately. An understanding of flow patterns is needed to apply the theory of fluid dynamics or heat transfer [2].

The study of two-phase flow can be studied from several sides, namely phase form, flow direction, channel orientation, channel size, and flow section shape. Two-phase flow can be liquid with liquid, gas with a liquid, liquid with solid, gas with solid and other phases. Based on the direction of the two-phase flow is divided into co-current and counter-current flow, whereas based on the position of the channel it is divided into upright, horizontal and incline flows. Based on the size of the channel, it is divided into large channels (conventional channel), narrow channels, mini channels, and microchannels. The parameters examined in a two-phase flow are the flow pattern and flow pattern map. In a two-phase flow in a mini-sized pipe, the fluid will have different properties with the two-
phase flow in a conventional or large-sized pipe. The difference is the surface tension in mini-sized pipes more dominant than in a conventional flow because the mini-channel flow has smaller the hydraulic diameter than conventional flow.

Mishima et al. [3] examine the two-phase water-air vertical flow on a rectangular channel. The channel used has a width of 40 mm and a length of 200 cm, with a variation of the gap that is used sequentially is 1, 2.4 and 5 mm. The research produced bubbly, slug, churn and annular flow patterns.

Wolk et al. [2] in his study compared two-phase flow pattern maps of vertical air-water on a circular, square, diamond and triangular duct, with a hydraulic diameter equivalent to 6 mm. This study concludes that channel geometry influences the transition of flow patterns.

Barnea et al. [4] in his research using a circular-section channel with diameters of 4, 6, 8.15, 9.85 and 12.3 mm. For the vertical flow, the channels used are 4 and 12.3 mm in diameter. This study produces a flow pattern map with intermittent flow distribution (consisting of elongated bubble, slug and churn flow patterns), dispersed bubble and annular.

A few researchers have only investigated the study of two-phase flow in mini-sized square channels. Based on the scientific understanding of the authors, there is still a disparity in the results of published investigations. From several studies on two-phase flow in mini-sized square channels that have been carried out, these studies produce various results. Even research for mini-sized square channels in oblique conditions has not been found. Visualization of the flow patterns that are formed and the depiction of flow pattern maps are important to show the characteristics that exist in the two-phase flow. The present research compares with previous studies in flow pattern maps, bubble velocities and void fractions for 5 mm mini-channels.

An important phenomenon in the two-phase flow is the flow pattern, the bubble velocity ($U_b$) of air and the void fraction ($\alpha$). Void fraction analysis was done by comparing the void fraction of the study with the void fraction correlations of the previous studies. Woldeemayat and Ghajar [5] show three such as Armand Correlation[6], Chisholm Correlation[7] and Homogen Correlation. Idea and Fukano [8] conducted an airflow investigation on two-phase flow in a mini-channel. Equation (1) predicts the bubble velocity using gas and liquid superficial velocity.

$$U_b = 1.2(U_G + U_L)$$

2. Experimental methods

The scheme of experimental apparatus used in this study is shown in Figure 1. The mixer used in this research is concentric stream mixer. In this type of mixer, the water enters from the axial direction while incoming air from the radial direction. The mixer is made a cubic resin with a 5 mm diameter waterhole and four air holes 1 mm in diameter on each side.

Air is supplied from the compressor to the mixer after passing the air flowmeter and the regulator with an average pressure of 0.5 MPa. In this study used air flowmeter with a measuring capacity of 0.1 - 1.0 liter/minute and 1 - 10 liters/minute. The water fluid is discharged from the 225 liters tank and pumped into the mixer after passing a water flowmeter with a measuring capacity of 0.1 - 1.0 liter/min and 1 - 10 liters/min. The test section is an acrylic square channel with a 5 mm hydraulic diameter.

The flow pattern identification in this study was done by visualization method at two-phase flow in the test section using high-speed video camera. The use of a high-speed video camera is intended so the form the flow pattern can be seen clearly with the frame speed of up to 1000 fps.

A video software is used to find the bubble/air velocity value from the video recorded by the high-speed video camera at each variation of the flow rate. In one video data, 20 samples of air bubble velocity measurements were obtained. An average of 20 samples was obtained as the bubble velocity ($U_b$) at certain variations of the flow rate.

3. Result and discussions

The discharge variation in this study was converted to the superficial velocity of each phase. The superficial velocity range of water and air used is 0.13 - 1.17 m/s and 0.33 - 7.31 m/s.
3.1. Flow Pattern

Referring to the flow pattern classification of Hewitt [9], the flow patterns found in this study are a bubble, slug, plug, and annular. The four flow patterns are shown as in Figure 2.

3.1.1. Bubble

The bubble flow pattern is characterized by small bubbles spreading in the liquid continuously. This pattern occurs at superficial low air velocity and superficial high water velocity. In a 5 mm diameter channel, bubble flow occurs at a superficial air velocity (\( \dot{J}_G \)) of 0.33 m/s and superficial water velocity (\( \dot{J}_L \)) of 1.17 m/s.

3.1.2. Slug

The slug flow pattern is characterized by a gas phase in the form of a 'bullet' bubble that fills the cross-sectional area of the channel. These slug bubbles flow with a stable pattern, separated by a liquid phase. In a 5 mm diameter channel, the slug flow occurs in the \( \dot{J}_G \) range of 0.33 - 2.93 m/s and the \( \dot{J}_L \) range is 0.13 - 1.17 m/s.

3.1.3. Churn

Churn flow patterns occur when the two-phase velocity on the slug flow is magnified. The pattern structure will become unstable and eventually will be destroyed, marked by the difficulty of finding the boundary between phases. In a 5 mm diameter channel, churn flow occurs in the \( \dot{J}_G \) range of 2.56 - 7.31 m/s and the \( \dot{J}_L \) range is 0.13 - 1.17 m/s.

Figure 1. The scheme of experimental apparatus [9]
3.1.4. Annular
The annular flow pattern of this study is formed by increasing air velocity, so the water will occupy the channel wall and form like a ring around the air that occupy the middle of the channel. This pattern occurs at high $J_G$. In the annular flow pattern, a thin layer of water is seen flowing along the inner wall of the pipe. In a 5 mm diameter channel, annular flow occurs in the $J_G$ range of 5.12 - 7.31 m/s and the $J_L$ range is 0.13 - 0.37 m/s.

3.2. Flow Pattern Maps
The flow pattern map is formed from the identification flow patterns according to the $J_G$ and $J_L$ values respectively. The proposed flow pattern map of this study is shown in Figure 3. Flow pattern map analysis is done by comparing the proposed flow pattern map with the flow pattern maps of previous researches. The proposed flow pattern map of the 5 mm channel was compared with the mini-channel flow pattern map reference and also compared to the reference flow pattern map of the conventional channel. It is intended to find out the trend of proposed flow pattern map of 5 mm channel to flow pattern map on both types of channel size. The proposed flow pattern map is compared with the flow pattern map from Barnea et al. [4] and Wolk et al. [2].

Comparison of the 5 mm flow pattern map with a reference flow pattern map is shown in Figure 4 and Figure 5. In this comparison, the 5 mm flow pattern map tends to be similar to the Wolk et al. [2] (mini channel). The difference with the Wolk’s map lies in the transition of slug pattern to churn. Differences in the map that occur can be caused by several factors such as the use of test section materials in several different studies. Some studies use a test section in the form of glass pipe and fiberglass, while this research use test section in the form of an acrylic channel. Another factor that is quite influencing the flow pattern results is the construction of each mixer of different research.

3.3. Bubble velocity
Research on the phenomenon of bubble velocity ever done one of them by Ide and Fukano [6]. Analysis of the bubble velocity is done by comparing between the air velocity of measurement using the software and the total superficial velocity input (J) using Equation (1). This comparison is shown in Figure 6. For the 5 mm channel, the accuracy of the data is 96% with an error tolerance of 20%.

3.4. Void Fraction
Another phenomenon of the two-phase flow is the presence of a void fraction ($\alpha$). Void fraction analysis has also been done a lot before. In this study, the void fraction of the measurements was compared against the three void fraction correlations. The comparisons of the void fraction of the
study of the three void fractional correlations are shown in Figure 7, Figure 8 and Figure 9, respectively. The accuracies of void fraction corresponding with the correlations of Armand, Homogen, and Chisholm at 20% error tolerance are 93%, 91% and 92%, respectively.

Figure 4. Comparison of flow pattern data with the flow pattern map of Wolk et al. [2]

Figure 5. Comparison of flow pattern data with the flow pattern map of Barnea et al. [4]

Figure 6. Comparison of bubble velocity of 5 mm square channel to Ide-Fukano’s correlation [8]

Figure 7. Comparison of a measured void fraction with the correlation of Armand [1]

Figure 8. Comparison of a measured void fraction with the Homogen correlation

Figure 9. Comparison of a measured void fraction with the correlation of Chisholm [4]
4. Conclusion
The air-water two-phase flow pattern formed on the vertical flow of a square channel with 5 mm hydraulic diameter with the air superficial velocity range \( (J_G) \) of 0.33 - 7.31 m/s and the superficial velocity of water \( (J_L) \) of 0.13 - 1.17 m/s are bubble, slug, churn and annular flow. The new flow pattern map formed in this study, so the 5 mm channel is categorized as a mini-channel. The bubble velocity of the study is in accordance with Ide and Fukano's correlation [9]. The void fraction measured in this study is in accordance with the void fraction correlation of Armand [6], Chisholm [7] and Homogen with a 20% error tolerance.

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