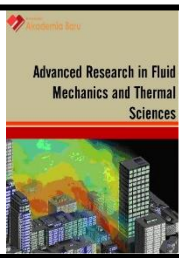
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



The Effect of Liquid Viscosity on The Gas-Liquid Two-Phase Flow Pattern in 45^o Inclined Capillary Pipe

Open Access

Sudarja[1,*], Sukamta[1], Deendarlianto[2], Indarto[2]

[1] Department of Mechanical Engineering, Faculty of Engineering, Universitas Muhammadiyah Yogyakarta, Jl. Brawijaya, Tamantirto, Kasihan, Bantul, Yogyakarta 55183, Indonesia
[2] Department of Mechanical and Industrial Engineering, Gadjah Mada University, Yogyakarta 55281, Indonesia

ARTICLE INFO

Article history:
Received 31 December 2019
Received in revised form 10 June 2020
Accepted 22 June 2020
Available online 3 September 2020

Keywords:
Gas-liquid two-phase flow; inclined capillary pipe; glycerol aqueous solution; liquid viscosity; flow pattern

ABSTRACT

The experiment on flow pattern of gas-liquid two-phase flow in 45^o inclined capillary channel was carried-out. The motivation was to obtain primary data and information of two-phase flow characteristics especially flow pattern. The test section was a 1.6 mm inner diameter and 130 mm length circular glass pipe, equipped with the optical correction box. A perpendicular entrance type mixer was used to mix both gas and liquid phase working fluids prior to test section. The high-speed camera was used to capture the two-phase flow. The captured video images were then analyzed to obtain the flow pattern. The range of gas and liquid superficial velocities were 0.025 - 66.3 m/s, and 0.033 - 4.935 m/s, respectively. The gas fluid was represented by dry air, while that of liquid was glycerol-aqua solution in various percentage, i.e. 0%, 10%, 20%, and 30%. The addition of glycerin to the liquid phase was intended to vary the liquid viscosities. As a result, it was found that both gas and liquid superficial velocities affected significantly to the two-phase flow configuration. Five flow patterns, namely: plug, slug-annular, churn, bubbly, and annular were observed, while the stratified flow was not obtained. The change of liquid viscosity affected to the configuration of flow pattern, especially in the liquid film thickness in annular flow and plug size and frequency in plug flow. Liquid viscosity also influenced to the shift of the transition line between flow patterns in the flow pattern map. The transition line between slug-annular flow and churn flow was shifted upper side when the liquid viscosity was increased. This condition caused by lower turbulence for higher liquid viscosity.

1. Introduction

Zhao and Bi [1] expressed that the application of the two-phase flow in the mini pipe is very wide, such as 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-

* *Corresponding author.*
E-mail address: sudarja@umy.ac.id

https://doi.org/10.37934/arfmts.75.1.4857

ray and other diagnostic devices. Furthermore, Kawahara *et al.,* [2] stated that the uses of those channels are in microelectronic circuits, aerospace and micro heat pipes, and bioengineering applications. Other authors reported the study results on the two-phase flow in small size channel among others Tsaoulidis *et al.,* [3], Hassan *et al.,* [4], Lee and Lee [5], Hanafizadeh *et al.,* [6], Chung and Kawaji [7], and Zhao *et al.,* [8].

The basic parameters in two-phase flow are flow pattern, void fraction, and pressure gradient. The variables which influence to the basic parameters are gas superficial velocity, liquid superficial velocity, viscosity and surface tension of working fluids. Some researchers investigated the effects of liquid viscosity to two-phase flow parameters. They are among others Fukano and Furukawa [9], Furukawa and Fukano [10], Sowinski and Dziubinski [11], Matsubara and Naito [12], Mc Neil and Stuart [13], Schmidt *et al.,* [14], Sadatomi *et al.,* [15], Sudarja *et al.,* [16], and Sukamta [17].

Fukano and Furukawa [9] carried-out a research on two-phase flow, using water and glycerol solution for annular flow in vertical pipe with inner diameter of 26 mm. They concluded that the increase of liquid viscosity affected to the increase of interface friction factor for the same gas phase Reynolds number. Furthermore, Furukawa and Fukano [10] also concluded that the liquid viscosity has a significant effect to the liquid film structure around big bubble in slug flow. In line with Fukano and Furukawa [9] and Furukawa & Fukano [10], Mc Neil and Stuart [13] also reported that, in the high liquid viscosity, the interface friction factor was significantly different to that in the low viscosity liquid.

On the other hand, the simulation studies on two-phase flow were also conducted by some researcher, such as Balthazar and Majeed [18], and Sukamta [19]. Balthazar and Majeed [18] compared the simulation with experimental results of heat transfer coefficient and pressure drop of ammonia refrigerant flow in a horizontal evaporator. As a result, for 100 kg/m^{2}s mass flux, the deviation of experimental and simulation of pressure drop and two-phase heat transfer coefficient were 3.52 % and 5.5 %, respectively. The comparison between simulation and experimental study of gas-liquid two-phase flow pattern in a horizontal small pipe was carried-out by Sukamta [19]. In this study water was mixed with glycerine in various percentage to vary the liquid viscosity. The results showed a good agreement between simulation and experimental data, for slug-annular, annular, and churn flow regime.

From the above-mentioned explanation, it can be concluded that no researcher has carried-out the experiment and discussed about the effect of liquid viscosity to the characteristics of two-phase flow in mini or micro channel in a large angle orientation. Therefore, study on the effect of liquid viscosity on the gas-liquid two-phase flow pattern in 45^o inclined capillary pipe was very important to be carried-out experimentally.

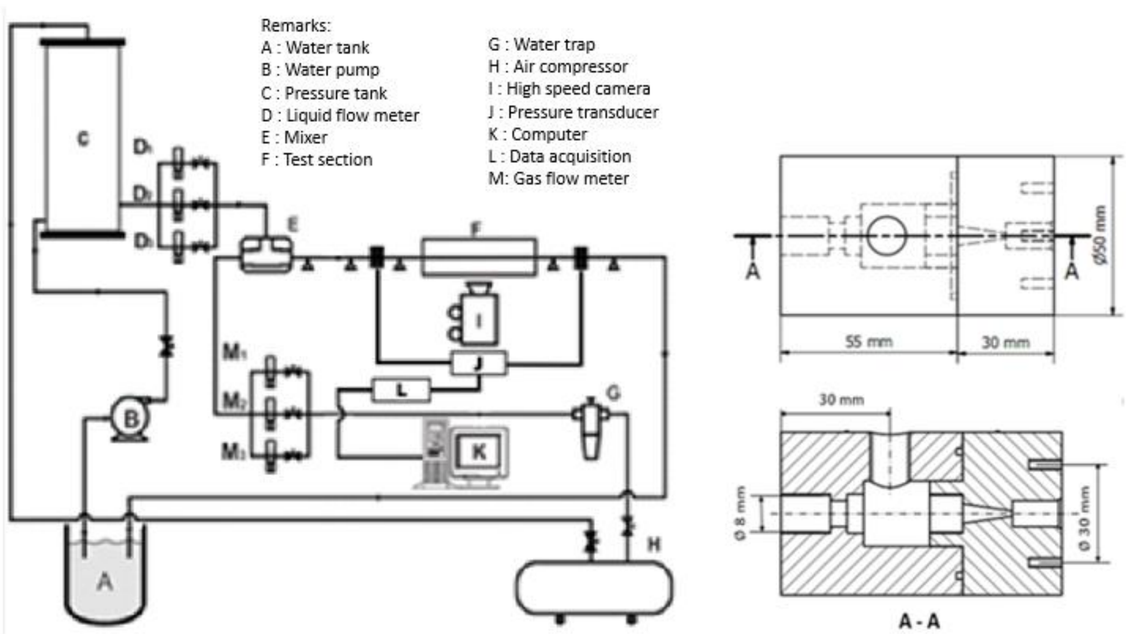
2. Methodology

Gas and liquids were used as working fluid in the present experiment. The dry air provided by air compressor which was equipped by water trap and dryer was used as gas phase fluid. While the liquid phase fluid was the mixture solution of water and glycerol in various percentage (10%, 20%, and 30%). The physical properties of air used in the present study (at 25^{o}C and 1 atmosphere) were density (ρ) of 1.163 kg/m^3, dynamic Viscosity (μ) of 1,8573 x 10^{-5} kg/(m.s), and kinematic Viscosity (ν) of 1.597 x 10^{-5} m^2/s. Meanwhile, those of liquid is shown in Table 1. The experimental apparatus used in present research is shown schematically in Figure 1, as also previously used and reported by Sudarja *et al.,* [16, 20]. As depicted in that figure, the liquid was pressed by the compressed air in the pressure vessel and then fed to the mixer and test section. The test section was a 1.6 mm inner diameter and 130 mm length circular glass pipe. The curve effect of pipe surface was eliminated by an optical correction box. A perpendicular entrance type mixer was used to mix both gas and liquid phase working fluid prior to test section.

Table 1
Physical properties of liquid

Fluids	Specific gravity	Kinematic viscosity [mm²/s]	Surface tension [mN/m]	Index
Water	1	0.84	71.03	W
Water+10% glycerin	1.036	1.33	67.97	GL10
Water+20% glycerin	1.062	2.32	60.93	GL20
Water+30% glycerin	1.084	2.36	60.87	GL30

Two kinds of liquid flow meter from Omega and TOKYO KEISO, with accuracy of ± 5 % and ± 3 %, respectively, were used to measure the liquid flow rate. Nikon J4 high-speed video camera with speed of 1200 fps and resolution of 640 x 480 pixel was employed to capture the flow images. The ranges of gas and liquid superficial velocities (J_G and J_L) were 0,025 – 66,3 m/s, and 0,033 – 4,935 m/s, respectively. The condition of the experiment was adiabatic.



(a) (b)

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

3. Results
3.1 Flow Pattern

Five distinctive flow patterns, namely plug, slug-annular, churn, annular, and bubbly were observed, while the stratified flow was not obtained. The absence of stratified or separated flow is caused by the dominance of surface tension effect against the gravitation one, as expressed by the previous researcher, such as Chung and Kawaji [7].

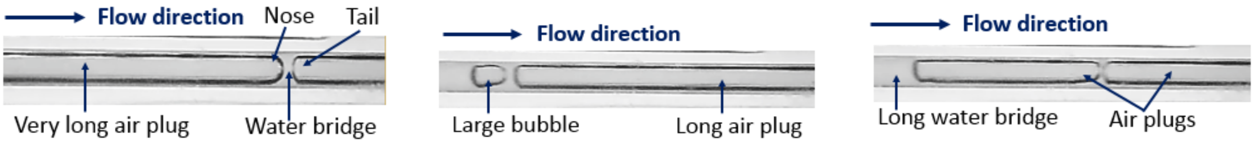
As reported by Sudarja *et al.,* [20], at low J_G and J_L, gas is restrained by liquid and forms gas bubble, before entering the mixing chamber. When the bubble size is large enough, the bubble pierces the liquid and enters to the mixing chamber then to the convergent zone in form of gas plug. In the mixer outlet, the long big bubble transforms into small plugs and enters the pipe intermittently with the water bridge. In this condition, the flow pattern formed is plug flow.

From this condition, when J_G is increased at a constant J_L, gas plugs penetrate and pierce the liquid bridges. As a result, the plugs merge and form a slug-annular flow pattern which characterized by the continuous ring flow with liquid neck in some points. From the slug-annular flow, when J_G is increased again, the liquid necks disappear and change to small ripples at the interface. The flow pattern is annular. The characteristic of annular flow is continuous annulus flow with a gas core in the center of channel. The appearance of the ripple at the interface indicates a slip phenomenon and also shear stress. From this condition, when J_L is increased (high J_G, high J_L), it causes flow turbulence and disrupts the flow in some region. This flow is called a churn flow. At low J_G and high J_L, gas enters to convergent zone in form of bubbles.

3.1.1 Plug flow

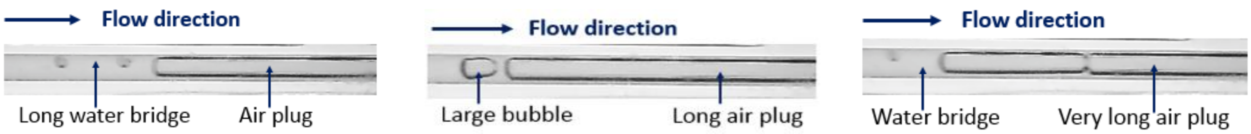
The slugs observed in the present study are in form of plugs, so that the flow is called as plug flow. Plug flow is occurred at low of both J_G and J_L, and at moderate J_G with low to moderate J_L. Fukano and Kariyasaki [21], and Saisorn and Wongwises [22] have ever reported that the plug length depended on J_G. Figure 2 and 3 illustrate the influences of J_G and J_L to the plug flow regime configuration in the present study. From those figures, it is clearly seen that parameter changes (increasing J_G or decreasing J_L) cause to form longer plug and shorter liquid bridge. This condition is an effect of the increasing void fraction, as ever been explained by Triplett *et al.,* [23].

The effect of liquid viscosity to the configuration of plug flow at the same J_G and J_L is illustrated in Figure 4. It is seen that, the plug length being shorter and the frequency being higher when the liquid viscosity is increased. Besides, the plug diameter is smaller when the liquid viscosity is increased, it means that the plug is surrounded by thin liquid film. This phenomenon has been reported previously by Sudarja *et al.,* [16].



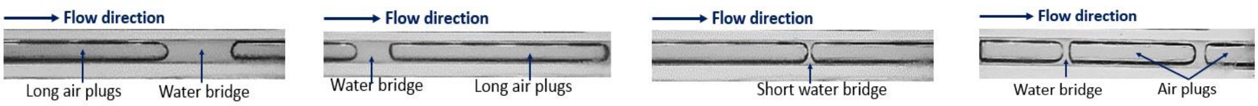
(a) $J_L = 0.232$ m/s (b) $J_L = 0.539$ m/s (c) $J_L = 0.89$ m/s

Fig. 2. Plug flow at $J_G = 0.207$ m/s and various J_L for GL10, 45° inclined orientation



(a) $J_G = 0.116$ m/s (b) $J_G = 0.207$ m/s (c) $J_G = 0.423$ m/s

Fig. 3. Plug flow at $J_L = 0.539$ m/s and various J_G for GL10, 45° inclined orientation



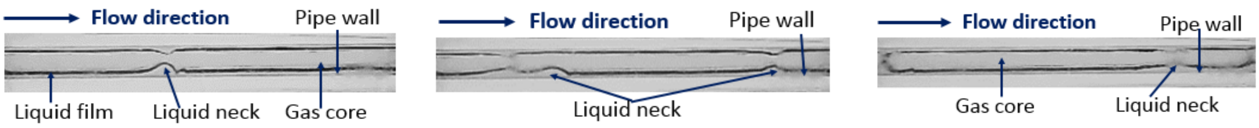
(a) W (b) GL 10 (c) GL 20 (d) GL 30

Fig. 4. Plug flow at $J_G = 0.116$ m/s and $J_L = 0.033$ m/s, for two-phase flow with various liquid viscosity, in 45° inclined orientation

3.1.2 Slug-annular flow

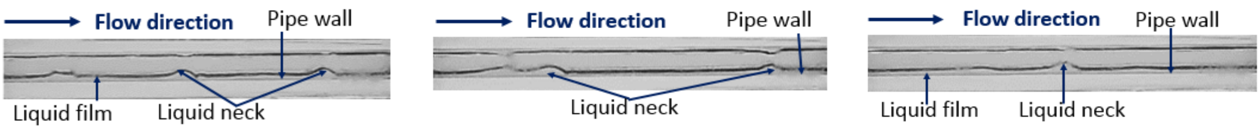
As previously explained, slug-annular flow is formed from plug flow when the gas superficial velocity is increased up to a certain value, where the flow of air can push and pierce the water bridge. The gas flows in the centre of channel, and the liquid flows at the pipe wall, and both fluids form a ring flow. The liquid neck is formed at certain points, which the liquid rings are thicker than those at the other points. Therefore, it is then called as slug-annular flow.

Figure 5 shows the effects of the increase of J_L, where it is seen that liquid neck frequency is higher and those size are longer. Besides, liquid film becomes thicker. On the contrary, higher J_G causes decreasing the frequency of the liquid necks and the size become shorter (Figure 6). In Figure 7, it can be concluded that the increased of liquid viscosity affects to the fewer and smoother liquid neck, also the thicker of liquid film.



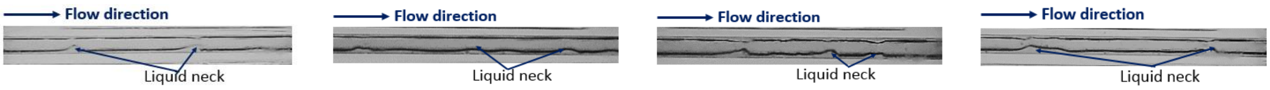
(a) $J_L = 0.091$ m/s (b) $J_L = 0.149$ m/s (c) $J_L = 0.232$ m/s

Fig. 5. Slug-annular flow at $J_G = 7$ m/s and various J_L for GL10, 45° inclined orientation



(a) $J_G = 4.238$ m/s (b) $J_G = 7$ m/s (c) $J_G = 9.62$ m/s

Fig. 6. Slug-annular flow at $J_L = 0.232$ m/s and various J_G for GL10, 45° inclined orientation

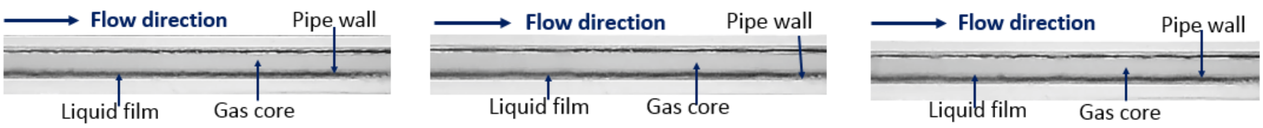


(a) W (b) GL 10 (c) GL 20 (d) GL 30

Fig. 7. Slug-annular flow at J_G = 4,238 m/s and J_L = J_L 0,091 m/s, for two-phase flow with various liquid viscosity, in 45° inclined orientation

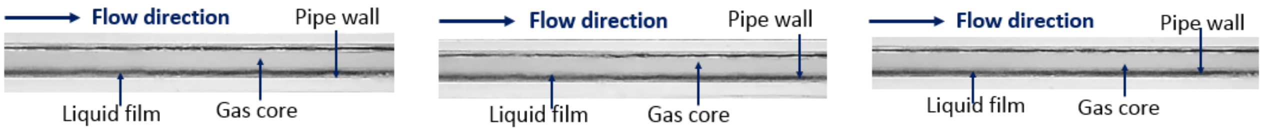
3.1.3 Annular flow

Annular flow or some authors called it ring flow, occurred at high J_G and low J_L. As shown in Figure 8, the increase of J_L causes the thicker liquid film, conversely, the higher J_G, the liquid film tends to thinner (Figure 9). The effect of the liquid viscosity to the annular flow pattern is exhibited in Figure 10. From that figure, it can be seen that the increase liquid viscosity lead to the thicker liquid film and lower ripples. This condition is caused by the high viscous force which almost be able to overcome the shear force at the flow interface.



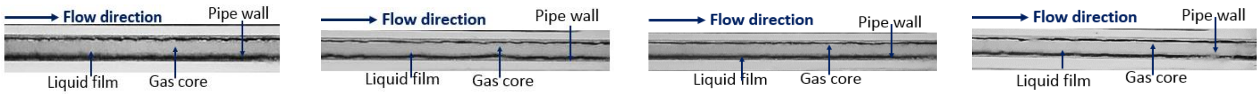
(a) $J_L = 0.091$ m/s (b) $J_L = 0.149$ m/s (c) $J_L = 0.232$ m/s

Fig. 8. Annular flow at $J_G = 50$ m/s and various J_L for GL 20, 45° inclined orientation



(a) J_G = 50 m/s (b) J_G = 58.05 m/s (c) J_G = 66.3 m/s

Fig. 9. Annular flow at J_L = 0,149 m/s and various J_G for GL 20, 45° inclined orientation

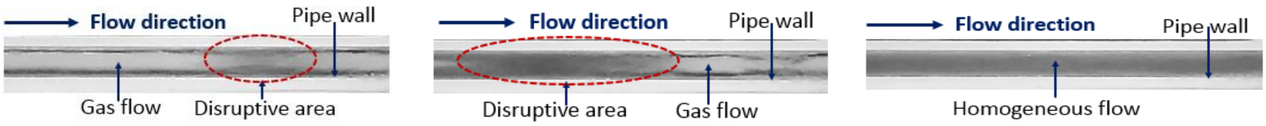


(a) W (b) GL 10 (c) GL 20 (d) GL 30

Fig. 10. Annular flow at J_G = 50 m/s and J_L = 0,149 m/s, for two-phase flow with various liquid viscosity, in 45° inclined orientation

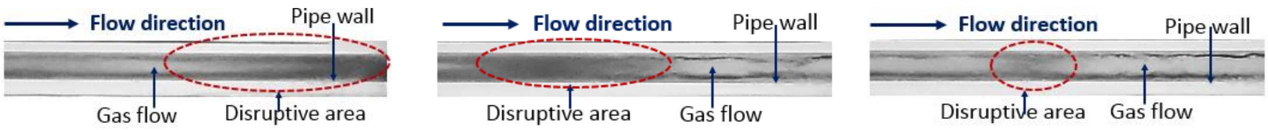
3.1.4 Churn flow

The characteristic of the churn flow is the appearance of disruption area or an irregular form in some point or sometimes along the flow. This flow is occurred at high both J_G and J_L. The increase of J_L in constant J_G tends to more disruptive area and the flow looked darker, as indicated in Figure 11. In contrary, the higher J_G in constant J_L caused the increase of void fraction and the flow is brighter (Figure 12). The liquid viscosity effect to the churn flow pattern is revealed in Figure 13. It can be seen clearly that at higher liquid viscosity the flow is not too disrupted. It is because of lower Reynolds number, so that the turbulence is also low.



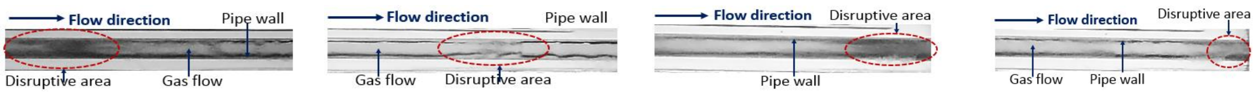
(a) J_L = 0.7 m/s (b) J_L = 2.297 m/s (c) J_L = 4.935 m/s

Fig. 11. Churn flow at J_G = 50 m/s and various J_L for GL 20, 45° inclined orientation



(a) J_G = 22.6 m/s (b) J_G = 50.05 m/s (c) J_G = 58.85 m/s

Fig. 12. Churn flow at J_L = 2.297 m/s and various J_G for GL 20, 45° inclined orientation

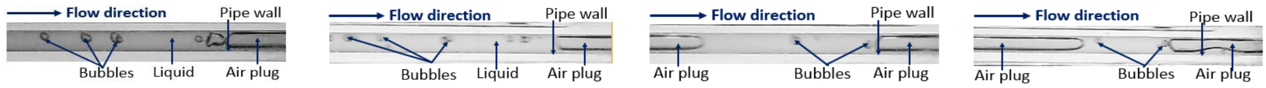


(a) W (b) GL 10 (c) GL 20 (d) GL 30

Fig. 13. Churn flow at J_G = 50 m/s and J_L = 2.297 m/s, for two-phase flow with various liquid viscosity, in 45° inclined orientation

3.1.5 Bubbly Flow

Bubbly flow is characterized by the appearance of gas bubbles with the diameter are same as or smaller than inner pipe diameter. This flow pattern is occurred at very low J_G and moderate to high J_L. In this study, the observed bubbles are in small diameter and appeared behind the long plug. It may be the effect of the incline orientation of the flow (45°). The effect of liquid viscosity to the configuration of bubbly flow is shown in Figure 14, where for higher liquid viscosity, the bubbles size is smaller and the distance of the plugs is being closer. Therefore, in the current experiment, the bubbly flow is not single flow, but mixed flow.



(a) W (b) GL 10 (c) GL 20 (d) GL 30

Fig. 14. Bubbly flow at J_G = 0.423 m/s and J_L = 0.89 m/s, for two-phase flow with various liquid viscosity, in 45° inclined orientation

3.2 Flow Pattern Map

The flow pattern map is plotted based on the flow pattern observed in each pair of J_G and J_L. The horizontal and vertical axis of the map are gas and liquid superficial velocities, respectively. Both axis are stated in logarithmic scale in order to accommodate the wide range of J_G and J_L, 0.025 – 66.3 m/s and 0.033 – 4.935 m/s, respectively (Figure 15). The effects of the liquid viscosity (W, GL 10, GL 20, and GL 30) to the transition lines are depicted in Figure 16. It is seen that flow patterns obtained in the present research (W, GL 10, GL 20, and GL 30) look similar, besides, the transition lines between correspond flow patterns are also in high similarity. However, there are some discrepancies of the transition lines, especially the transition line between bubbly flow and plug flow, and between slug-annular flow and churn flow.

Compared to the previous paper, the result of the present study is in a good agreement with Triplett *et al.,* [23], Chung and Kawaji [7], Sudarja *et al.*, [20] and Sukamta and Sudarja [24] in term of flow patterns observed and transition line configuration in the flow pattern map. However, it appears a little discrepancy concerning area of each flow pattern in the map. Compared to Sur and Liu [25], it is seen that the present study is in fairly agreement. This is maybe caused by the difference of pipes diameter, where they used much smaller pipes (0.324 mm and 0.18 mm).

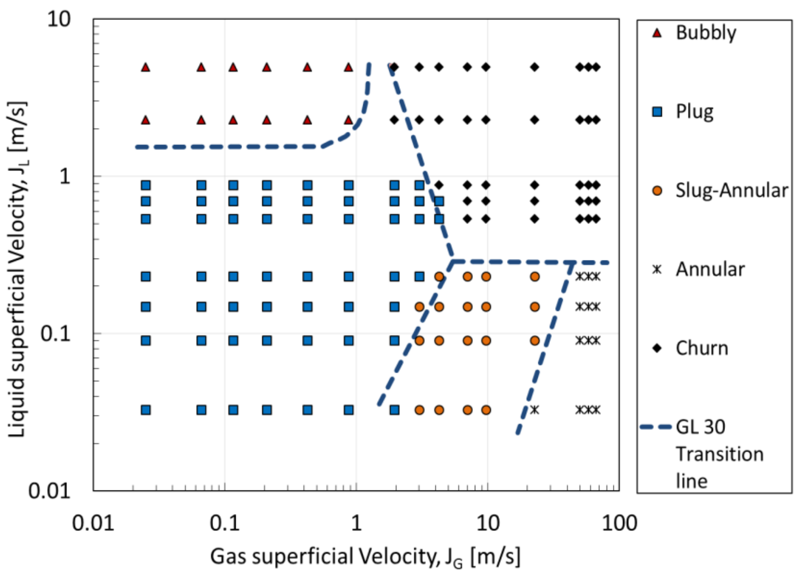


Fig. 15. Flow pattern map of G 30 gas-liquid two-phase flow

The transition boundary line between slug-annular and churn flow in Figure 16 shifts to upper side or toward higher J_L when the liquid viscosity is increased. It means that the churn flow area is narrower or in the other words, the churn flow is more difficult to form when the liquid viscosity is higher. This condition is caused by the very low turbulence, and the viscous force is more dominant than the inertia force. From the comparation, it can be stated that J_G, J_L, liquid viscosity, and channel size affect to the flow pattern formed.

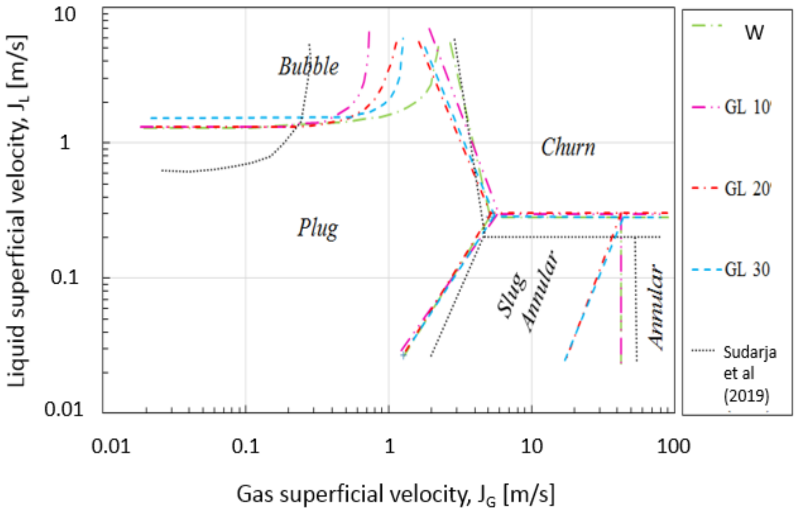


Fig. 16. Flow pattern map comparison for various liquid viscosity and against the previous study

4. Conclusions

The experimental study on the gas-liquid two-phase flow pattern in mini channel was performed in adiabatic condition. The ranges of gas and liquid superficial velocities were 0.025-66.3 m/s and 0.033-4.935 m/s, respectively. The working fluids employed in the present study were air (as gas fluid) and solution of water and Glycerine in various percentage (as liquid fluid). The result of the research can be summarized as follows

i. Plug, slug-annular, churn, annular, and bubbly flow patterns were observed, while the stratified flow was not appeared. Both J_G and J_L determine the flow pattern formed.
ii. The orientation of channel slightly affects to the configuration of bubbly flow.
iii. Liquid viscosity influences the flow configuration, especially in the liquid film thickness in annular flow and plug size and frequency in plug flow.
iv. In term of flow pattern map, the transition lines configuration and the flow pattern area in maps are similar, even though for different liquid viscosity, except slightly shift of some transition lines. As shown in the map, the transition line between slug-annular and churn flow is shifted upper side when the liquid viscosity is increased. This condition shows that the higher liquid viscosity tends to lower turbulence and the viscous force is more dominant then the inertia force.

Acknowledgement
The authors would like to express their appreciation to The Ministry of Research and Higher Education of Indonesia for funding this research, and also to Mr. Windy Prasetyo for his contribution in preparing the experiment rig and collecting data of this study.

References

[1] Zhao, T. S., and Q. C. Bi. "Co-current air–water two-phase flow patterns in vertical triangular microchannels." *International Journal of Multiphase Flow* 27, no. 5 (2001): 765-782. https://doi.org/10.1016/S0301-9322(00)00051-3

[2] Kawahara, A., PM-Y. Chung, and M. Kawaji. "Investigation of two-phase flow pattern, void fraction and pressure drop in a microchannel." *International journal of multiphase flow* 28, no. 9 (2002): 1411-1435. https://doi.org/10.1016/S0301-9322(02)00037-X

[3] Tsaoulidis, Dimitrios, Valentina Dore, Panagiota Angeli, Natalia V. Plechkova, and Kenneth R. Seddon. "Flow patterns and pressure drop of ionic liquid–water two-phase flows in microchannels." *International Journal of Multiphase Flow* 54 (2013): 1-10. https://doi.org/10.1016/j.ijmultiphaseflow.2013.02.002

[4] Hassan, I., M. Vaillancourt, and K. Pehlivan. "Two-phase flow regime transitions in microchannels: a comparative experimental study." *Microscale Thermophysical Engineering* 9, no. 2 (2005): 165-182. https://doi.org/10.1080/10893950590945049

[5] Lee, Chi Young, and Sang Yong Lee. "Influence of surface wettability on transition of two-phase flow pattern in round mini-channels." *International Journal of Multiphase Flow* 34, no. 7 (2008): 706-711. https://doi.org/10.1016/j.ijmultiphaseflow.2008.01.002

[6] Hanafizadeh, Pedram, Soheil Ghanbarzadeh, Arash Nouri Gheimasi, and Mohammad Hassan Saidi. "Experimental investigation of air-water two phase flow regime in vertical mini pipe." In *International Conference on Nanochannels, Microchannels, and Minichannels*, vol. 54501, pp. 1411-1417. 2010. https://doi.org/10.1016/j.scient.2011.07.003

[7] Chung, PM-Y., and M. Kawaji. "The effect of channel diameter on adiabatic two-phase flow characteristics in microchannels." *International journal of multiphase flow* 30, no. 7-8 (2004): 735-761. https://doi.org/10.1016/j.ijmultiphaseflow.2004.05.002

[8] Zhao, Y., H. Yeung, E. E. Zorgani, A. E. Archibong, and L. Lao. "High viscosity effects on characteristics of oil and gas two-phase flow in horizontal pipes." *Chemical Engineering Science* 95 (2013): 343-352. https://doi.org/10.1016/j.ces.2013.03.004

[9] Fukano, T., and T. Furukawa. "Prediction of the effects of liquid viscosity on interfacial shear stress and frictional pressure drop in vertical upward gas–liquid annular flow." *International journal of multiphase flow* 24, no. 4 (1998): 587-603. https://doi.org/10.1016/S0301-9322(97)00070-0

[10] Furukawa, T., and T. Fukano. "Effects of liquid viscosity on flow patterns in vertical upward gas–liquid two-phase flow." *International journal of multiphase flow* 27, no. 6 (2001): 1109-1126. https://doi.org/10.1016/S0301-9322(00)00066-5

[11] Sowiński, J., and M. Dziubiński. "The effect of liquid viscosity on the void friction in a two-phase gas-liquid flow in narrow mini-channels." (2007).

[12] Matsubara, Hiroaki, and Kiyoshi Naito. "Effect of liquid viscosity on flow patterns of gas-liquid two-phase flow in a horizontal pipe." *International Journal of Multiphase Flow* 37, no. 10 (2011): 1277-1281. https://doi.org/10.1016/j.ijmultiphaseflow.2011.08.001

[13] McNeil, David A., and Alastair D. Stuart. "The effects of a highly viscous liquid phase on vertically upward two-phase flow in a pipe." *International journal of multiphase flow* 29, no. 9 (2003): 1523-1549. https://doi.org/10.1016/S0301-9322(03)00122-8

[14] Schmidt, J., H. Giesbrecht, and C. W. M. Van der Geld. "Phase and velocity distributions in vertically upward high-viscosity two-phase flow." *International Journal of Multiphase Flow* 34, no. 4 (2008): 363-374. https://doi.org/10.1016/j.ijmultiphaseflow.2007.10.013

[15] Sadatomi, Michio, Akimaro Kawahara, Masatoshi Matsuo, and Katsuhiro Ishimura. "Effects of surface tension on two-phase gas-liquid flows in horizontal small diameter pipes." *Journal of Power and Energy Systems* 4, no. 2 (2010): 290-300. https://doi.org/10.1299/jpes.4.290

[16] Sudarja, Farid Jayadi, Indarto, Deendarlianto, and Adhika Widyaparaga. "The effect of liquid viscosity on the gas-liquid two-phase flow pattern in horizontal mini-channel." In *AIP Conference Proceedings*, vol. 2001, no. 1, p. 030010. AIP Publishing LLC, 2018. https://doi.org/10.1063/1.5049982

[17] Sukamta, Sukamta,. "Two-Phase Flow Pattern of Air-Water with Low Viscosity in a 5-Degree Slope of a Capillary Pipe." *CFD Letters* 12, no. 2 (2020): 115-123.

[18] Balthazar, Pravinth, and Muzathik Abdul Majeed. "Simulation analysis of two-phase heat transfer characteristics in a smooth horizontal ammonia (R717) evaporator tube." *CFD Letters* 10: 49-58.
[19] Sukamta, Sukamta. "Computational fluid dynamics (CFD) and experimental study of two-phase flow patterns gas-liquid with low viscosity in a horizontal capillary pipe." *CFD Letters* 11 (2019): 16-23.
[20] Haq, Aqli, and Adhika Widyaparaga. "Experimental study on the flow pattern and pressure gradient of air-water two-phase flow in a horizontal circular mini-channel." *Journal of Hydrodynamics* 31, no. 1 (2019): 102-116. https://doi.org/10.1007/s42241-018-0126-2
[21] Fukano, Tohru, and Akira Kariyasaki. "Characteristics of gas-liquid two-phase flow in a capillary tube." *Nuclear Engineering and Design* 141, no. 1-2 (1993): 59-68. https://doi.org/10.1016/0029-5493(93)90092-N
[22] Saisorn, Sira, and Somchai Wongwises. "Flow pattern, void fraction and pressure drop of two-phase air–water flow in a horizontal circular micro-channel." *Experimental Thermal and Fluid Science* 32, no. 3 (2008): 748-760. https://doi.org/10.1016/j.expthermflusci.2007.09.005
[23] Triplett, K. A., S. M. Ghiaasiaan, S. I. Abdel-Khalik, A. LeMouel, and B. N. McCord. "Gas–liquid two-phase flow in microchannels: part II: void fraction and pressure drop." *International Journal of Multiphase Flow* 25, no. 3 (1999): 395-410. https://doi.org/10.1016/S0301-9322(98)00054-8
[24] Sukamta, Sukamta, and S. Sudarja. " The Significant Effect of Liquid Viscosity on Two-Phase Flow Pressure Gradient in Mini Channel with Slope of 15o against Horizontal." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 70, No 2 (2020): 116-123. https://doi.org/10.37934/arfmts.70.2.116123
[25] Sur, Aritra, and Dong Liu. "Adiabatic air–water two-phase flow in circular microchannels." *International Journal of Thermal Sciences* 53 (2012): 18-34. https://doi.org/10.1016/j.ijthermalsci.2011.09.021