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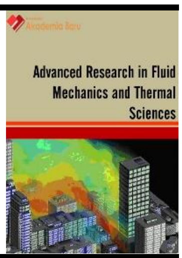

Investigation of the Effect of Fluids Superficial Velocity on Initiation and Development of Slug Flow in a Horizontal Hydraulics Pipe

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ABSTRACT

The aim of this study is to investigate the effect of fluids superficial velocity on the characteristics of two-phase slug flow in a horizontal hydraulics pipe covering slug flow initiation and development. Air and water were employed as the working fluids. Slug flow characteristics were visually observed at 25D and 200D in a 19 mm internal diameter of acrylic pipe for the initiation and fully developed slug flow conditions, respectively. Flow visualization was taken using high speed video cameras at 400 fps and then analyzed using image processing method. Based on the flow pattern characteristics, several slug flow initiation mechanisms were obtained. Under the investigated conditions, at low to medium air superficial velocity (J_G) with low to high water superficial velocity (J_L), slug flow initiation mechanisms consisted of wave growth, hydraulic jump, blockage, and slug decaying. While wave initiation, wave formation, disturbance, wave coalescence, and incompletely developed slug mechanisms were observed at medium to high J_G with low to high J_L. After slug flow was fully developed, it was found that the higher the water superficial velocity resulted in lower void fraction and higher slug frequency. In the meantime, pressure drop and liquid slug velocity increased considerably with the increase of both J_G and J_L. Maximum pressure drop of 8.35 kPa/m occurred at J_L of 2.00 m/s and J_G of 3.76 m/s. The highest slug frequency of 6.67 1/s was observed at J_L of 2.00 m/s and J_G of 2.12 m/s. This information is important for designing fluid flow in horizontal hydraulics pipes and for consideration in predicting the development of the slug flow in order to avoid the negative impact of slug flow in industrial applications.

Keywords:
Superficial velocity; slug flow; initiation; fully developed; characteristic; horizontal hydraulics pipe

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1. Introduction

Two-phases flow in a horizontal hydraulics pipe is the part of multi-phases flow. Flow from these different phases is commonly found both in daily life and in industrial processes [1,2]. One common form of two-phases flow is slug flow in which the liquid flows intermittently along the pipes in a concentrated mass. One of the characteristics of slug flow is the high fluctuation of velocity and local pressure of the gas and liquid phases caused by friction between the liquid slug at the top of the pipe, the liquid slug at the bottom of the pipe and slippage between phases. In addition to causing high pressure losses, local pressure differences that fluctuate in large numbers also result in pipes and structures damage such as corrosion and blasting [3,4]. Thus, the presence of slug flow needs to be avoided and controlled to prevent damage to the pipe.

Several mechanisms of wave growth have been reported including Kelvin-Helmholtz instability theory or Inviscid Kelvin-Helmholtz (IKH) [5], Viscous Long Wavelength (VLW) instability [6], and slug stability theorem [7,8]. In general, these concepts explain slug flow in the high superficial velocities analytically with some assumptions, so that it did not detailly explain the slug flow formation. It should be noted that study of slug flow experimentally could be essentially needed to provide complete information for better clarification of understanding of slug flow mechanisms [9,10].

Slug flow mechanisms typically include formation, growth, and fully developed flow condition. Initially, slug flow originated from a small wave at the interface of gas–liquid caused by the difference of liquid and gas fluids velocity. Slug flow can be found at any point in unstable flow. As the slug grows, the height of the water level in the pipe increases due to the rapid frequency of slug formation [11]. However, to find out the behavior of slug flow, it is necessary to understand the mechanism and characteristic of both initiation and fully developed slug flow conditions such as wave growth, wavelength, liquid hold-up, pressure drop, void fraction, as well as slug frequency. The understanding of the slug initiation mechanism is very important in pipeline design. For this purpose, a number of literatures have been published that investigate slug flow initiation mechanism as well as fully developed slug flow at various conditions. Studies on slug flow formation mechanism have been described by several researchers such as Dukler and Hubbard [12], Ruder *et al.,* [13], Gu and Guo [14], and Nieckele *et al.,* [15]. Thermal effect on slug flow formation [16] as well as hydrodynamic behavior of gas-liquid (air-water) two-phases flow near the transition to slug flow in a horizontal pipe [17] have also been informed. Nevertheless, there are insufficient information related to investigation of slug flow initiation. Recently, Dinaryanto *et al.,* [10] investigated initiation and fully developed air and water slug flow using acrylic pipe of 26 mm internal diameter and 10 m length. Slug flow initiation was observed at 0-75D whereas fully developed slug flow was studied at 75-210D to examine the mechanism of wave growth, wave distribution, and slug frequency formed along the pipe using 2 high speed cameras. Conte *et al.,* [18] also studied characterization of slug initiation for horizontal air-water two-phase flow using acrylic tubes with 26 mm internal diameter and provided distribution and statistical parameters for bubble length, slug length, bubble velocity, slug frequency and unit-cell frequency of slug initiation. However, it is believed that due to complex process of slug flow, there are others initiation mechanisms that need clear clarification. In addition, void fraction and liquid slug velocity with regard to development of slug flow are others important parameters to be revealed particularly in a relatively small pipe diameter.

Based on the above description, although studies of initiation and fully developed slug flow in horizontal hydraulics pipes have been an interesting topic both theoretical and practical, the slug flow formation is so complex by its transient nature and the multi-dimensional dynamic process as there are many parameters and characteristics involved. Therefore, this study is performed to investigate the initiation and development of slug flow characteristics covering formation mechanisms, void fraction, liquid slug velocity, pressure drop, slug frequency etc. in a small horizontal pipe. In addition, slug flow characteristics were studied at different ranges of superficial velocities of air and water. This work actually elucidated slug flow formation mechanism in crucial conditions, thus complementing the slug flow information in previous studies. Thereby, slug flow characteristics obtained in this work are highly essential for understanding the slug flow mechanisms that are important for piping design to prevent pipe damage.

2. Methodology

A schematic representation of the experimental apparatus is shown in Figure 1. This study used a transparent acrylic pipe with an inner diameter of 19 mm. The test section length was 5,800 mm to ensure the slug flow is well developed. The apparatus was equipped with a mixer to accommodate the formation of two-phases flow in the horizontal pipe as used in previous studies [10,19]. The mixer was designed in the form of a tube which has a splitter in the center area made of acrylic with a thickness of 3 mm. In this work, water and air were employed as the working fluids. The air and water were supplied from the top side and bottom side of the splitter, respectively into the inlet. A semi jet water pump with a maximum capacity of 50 lpm and a total head of 41 m was used for water circulation. While, to accommodate pressurized-air flowed into the test section, a compressor with a maximum pressure of 80 bar was applied. Some valves and flow meters for water and air regulation were also used. There were two types of flow meters i.e. 0–4 lpm and 0–100 lpm for water, and 0–10 lpm and 0–60 lpm for air measurements.

The experimental apparatus was also completed with two correction boxes and LED lamps to facilitate data collection and visualization of two-phases fluid flow study both at the initiation and the development sections. Each correction box used is made of 5 mm acrylic sheet with a size of 410 mm x 75 mm x 75 mm. The correction box is used to minimize the refractive indices difference between the fluids and tube wall material so that the image distortion of water-air flowing inside the tube can be reduced. For this purpose, the correction boxes were filled by water that had an almost similar to acrylic's refractive index. Two high-speed video cameras were used to facilitate slug flow visualization at the initiation and development flow sections.

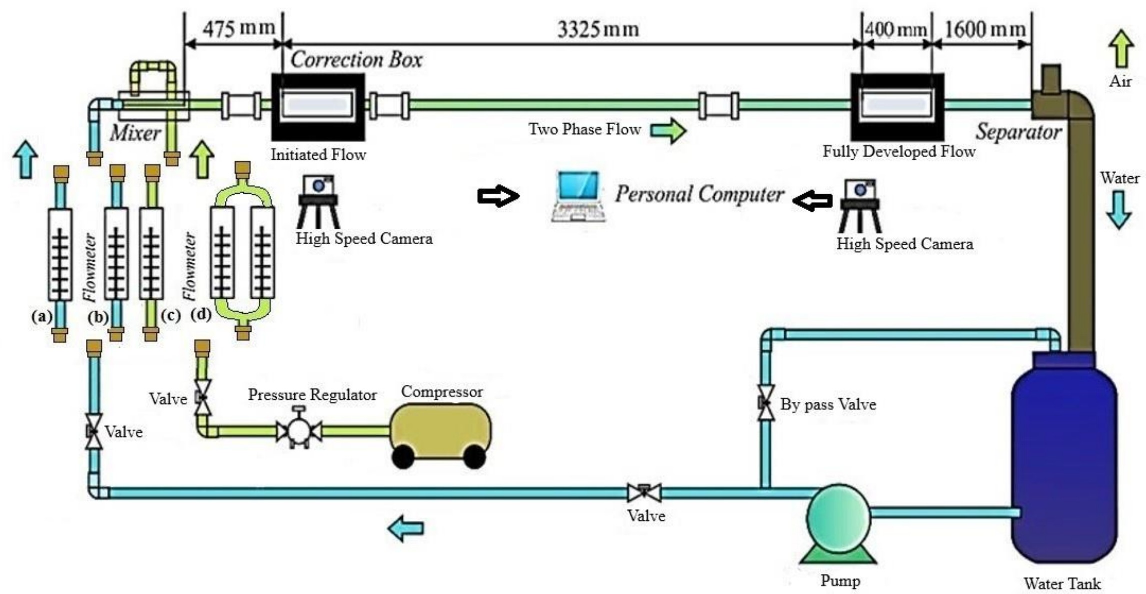

Fig. 1. Schematic diagram of the experimental apparatus

The visualization experiment was carried out at various air superficial velocity (J_G) of 2.12 to 3.76 m/s and water superficial velocity (J_L) of 0.88 to 2 m/s. These experimental conditions were plotted in the Mandhane flow pattern map [20] to ensure the superficial fluid velocities range is in the slug flow pattern category as illustrated in Figure 2. In each experiment, the water and air were supplied at a predetermined superficial velocity. After steady condition has been reached, the air-water flow visualization data was taken at the test section spaced of 25D to 46D for initiation of slug flow and 200D to 221D for fully-developed slug flow using two high-speed video cameras with a frame rate of 400 fps and a resolution of 640 x 240 pixels as shown in Figure 1. These conditions are able to record or capture 42-182 frames in each test section under the investigated conditions. The video camera recorded data was then processed using Virtual Dub and CorelDraw software in order to evaluate slug flow initiation and development characteristics including void fraction, pressure drop, slug frequency, and liquid slug velocity.

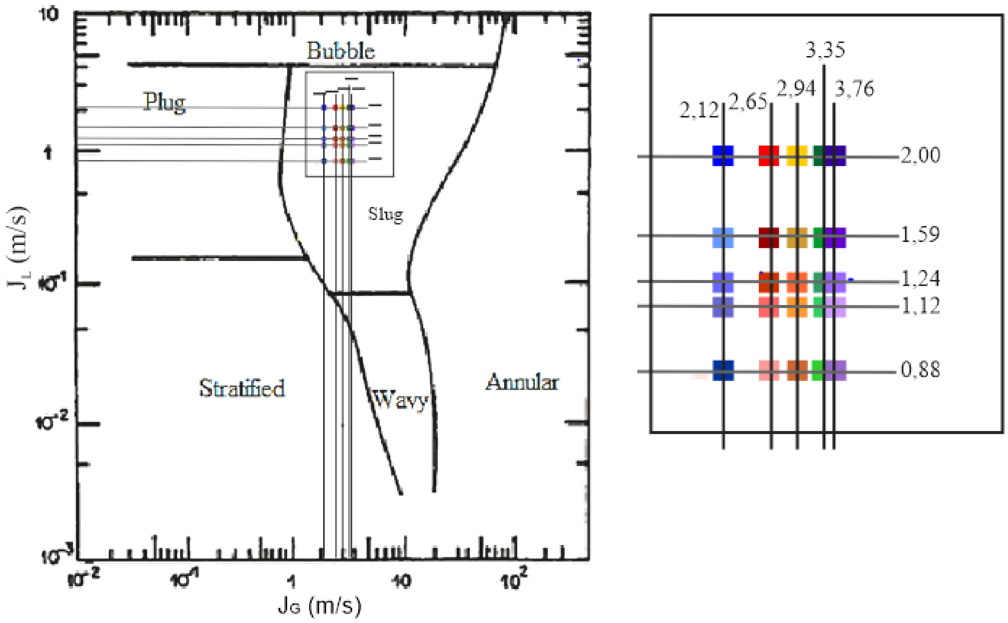

Fig. 2. Plot of experimental conditions in the Mandhane flow pattern map

The void fractions in this work were measured from the captured picture in each investigated condition as shown in Figure 3. Based on the figure, the void fraction (α) was calculated as follows

$$A_w = \frac{\theta\ x\ \pi\ x\ r^2}{360^o} - \frac{\sin(\theta)\ x\ r^2}{2} = \frac{\theta\ x\ 3.14\ x\ 0.0095^2}{360^o} - \frac{\sin(\theta)\ x\ 0.0095^2}{2} \quad (1)$$

$$\alpha = \frac{A - A_w}{A} \quad (2)$$

where A_w is the wetted area and A is the total area. The measured void fraction was then compared to empirical correlations given in previous literature.

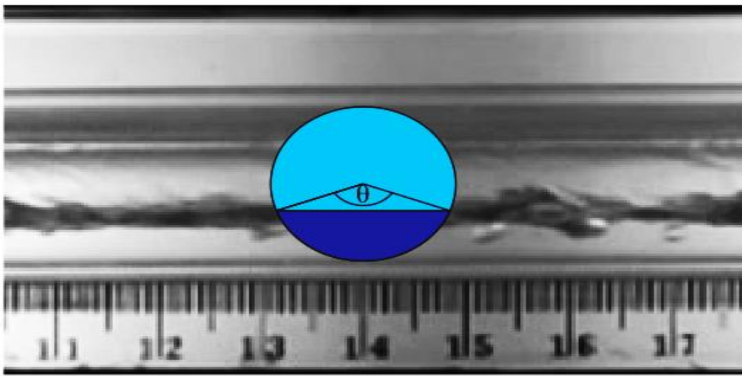

Fig. 3. Visual data processing for void fraction measurement

3. Results and Discussion

3.1 Visualization of Initiation and Development of Slug flow

This research involved slug formation mechanism, started by wave growth or Kelvin-Helmholtz mechanism as given in Figure 4 which occurred at J_G of 2.12 m/s and J_L of 0.88 m/s. It could be observed that wave growth was formed as the increase of air superficial velocity at constant water superficial velocity. At a constant water superficial velocity, the increase of air superficial velocity ignited the wave coalescence as revealed in Figure 5 (J_G=2.94 m/s and J_L=0.88 m/s). The formed wave fused with other waves thus combined and generated wave coalescence.

At high water superficial velocity (J_L>0.88 m/s), slug formation mechanism was influenced by both development of a single wave and wave merging. Disturbance was also found at inlet mixer area at high water superficial velocity which in turn affecting slug formation. At high water superficial velocity (J_L>0.88 m/s) and low air superficial velocity (J_G<3 m/s), slug was formed through wave development as shown in Figure 6 (J_G=2.65 m/s and J_L=1.59 m/s). At high J_L, the unstable flow triggered slug decaying that generated a high number of slugs in the initiation area than that of in the fully developed area.

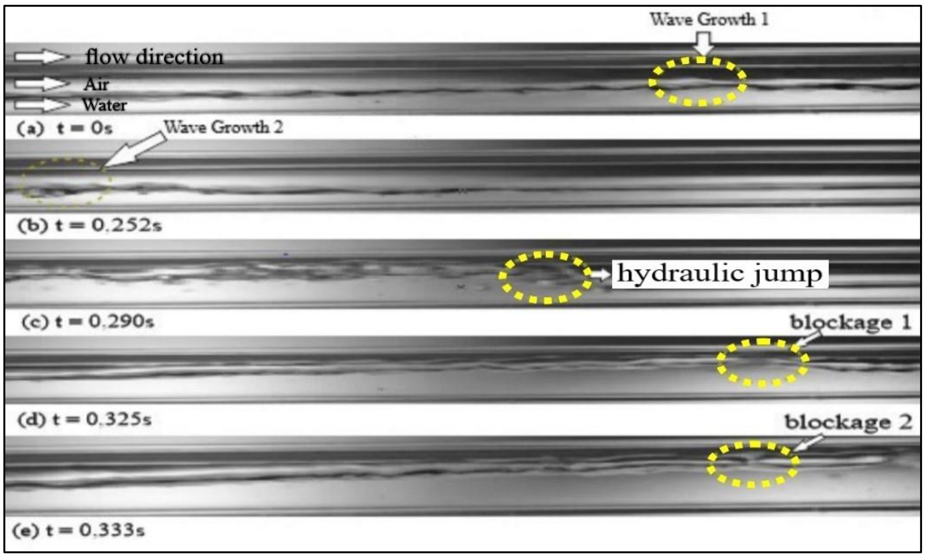

Fig. 4. Visualization of slug flow initiation with Kelvin-Helmholtz mechanism at 25D (J_G=2.12 m/s and J_L=0.88 m/s)

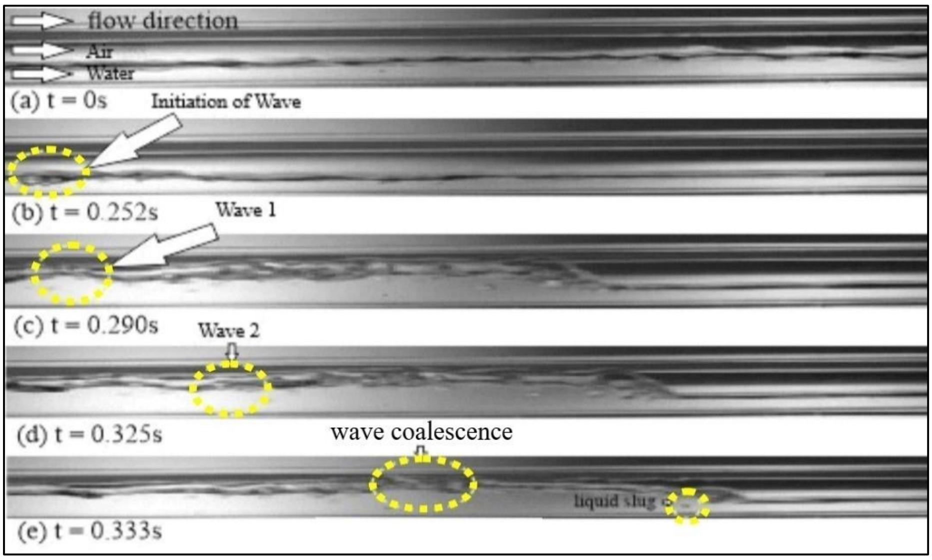

Fig. 5. Visualization of slug flow initiation with wave coalescence mechanism at 25D (J_G=2.94 m/s and J_L=0.88 m/s)

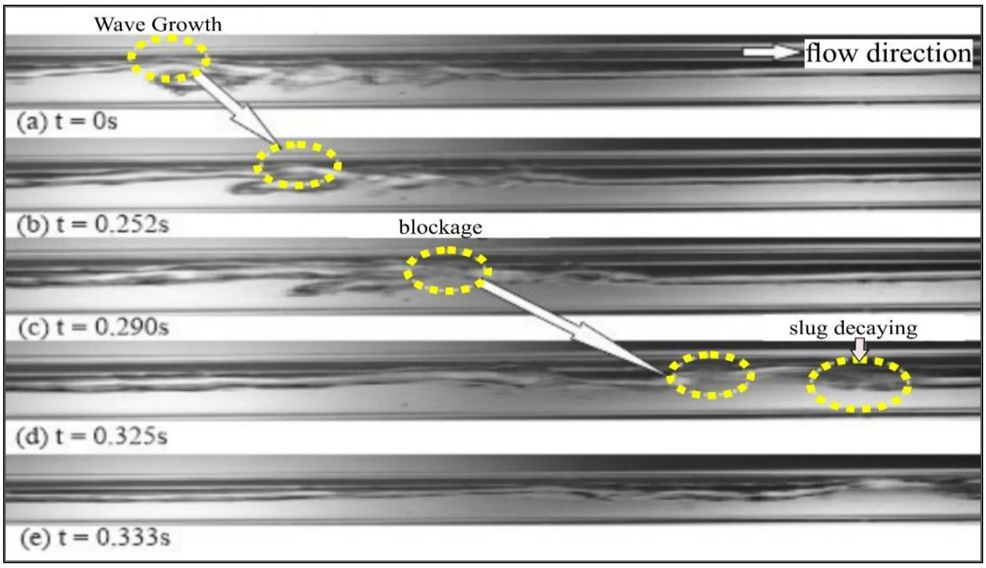

Fig. 6. Visualization of slug flow initiation at high water superficial velocity and low air superficial velocity at 25D (J_G=2.65 m/s and J_L=1.59 m/s)

When air superficial velocity increased (J_G>3 m/s), turbulence level and the amount of water at inlet area also increased. It resulted in the increase of disturbance level at inlet area which subsequently would give a major influence on slug formation. The phenomenon is illustrated in Figure 7 for J_G=3.35 m/s and J_L=1.59 m/s. It can be seen in the beginning of wave formation, a wave disturbance appeared, followed by another wave. The wave coalescence was then formed that resulted in slug formation, marked by the appearance of slug with slug nose and slug tail. However, the slug in initiation area of 25D-46D was not completely formed. While in development area (200D-221D), along with the increase of water superficial velocity and air superficial velocity, slug was completely formed.

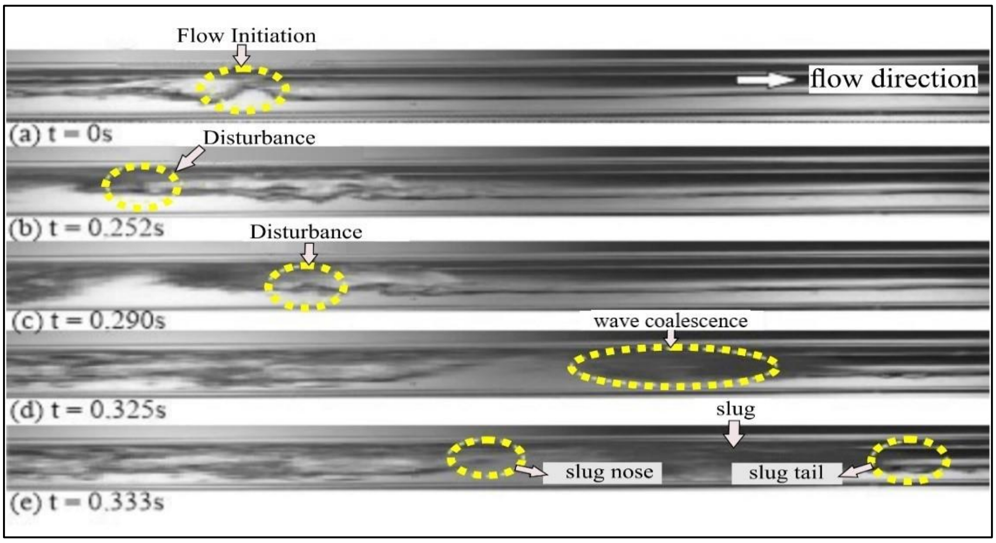

Fig. 7. Visualization of slug flow initiation at high water superficial velocity and high air superficial velocity at 25D (J_G=3.35 m/s and J_L=1.59 m/s)

Observation in the development flow area is shown in Figure 8 for a low J_G value (J_G=2.12 m/s). Slug flow consisted of an elongated bubble and a liquid slug with several tiny bubbles in it. This is in accordance with slug unit scheme of Dukler and Hubbard [12].

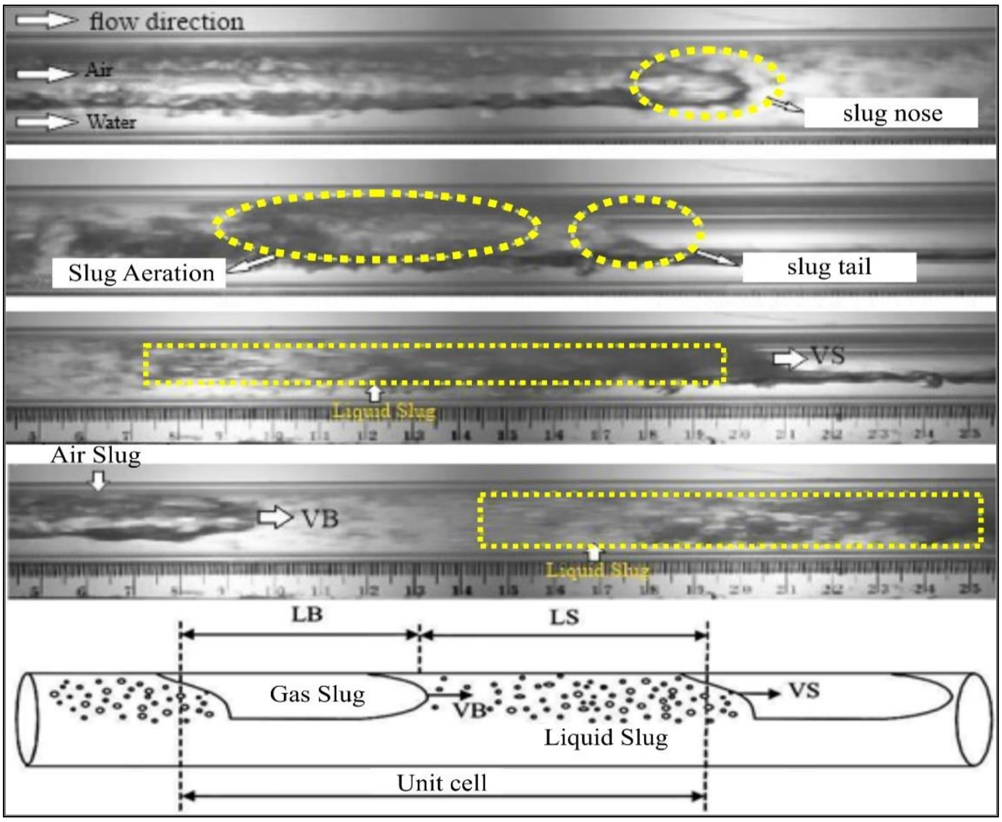

Fig. 8. Visualization of slug flow at developed area at 200D for low air superficial velocity and low water superficial velocity (J_G=2.12 m/s and J_L=0.88 m/s) in accordance to Dukler and Hubbard [12] scheme

Along with the progressed flow, the slug length increased due to the velocity difference between the nose and tail of the slug itself. At high water superficial velocity, slugs tended to reach a constant length faster. This was identified by the same velocities of nose and tail. As the increased of air superficial velocity, for example at J_G=2.94 m/s, the number of bubbles increased and formed dispersed slug in the tail of liquid slug, as shown in Figure 9.

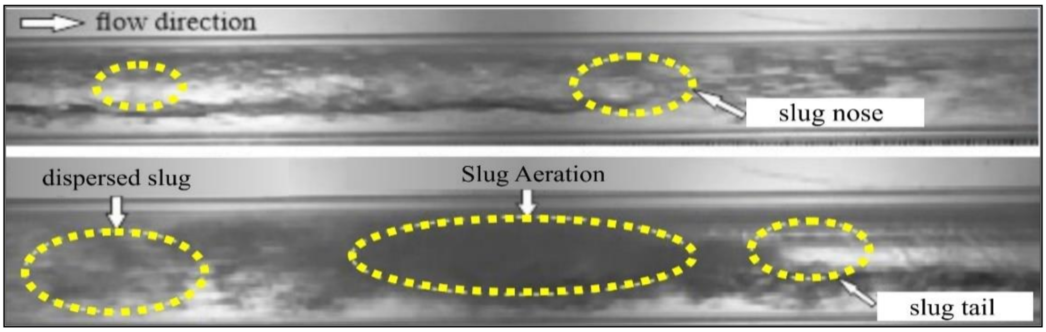

Fig. 9. Visualization of fully developed slug flow at 200D at J_G=2.94 m/s and J_L=0.88 m/s

Slug flow was initiated by waves development, blockage in pipes, and liquid slug followed by gas slug. Figure 10 shows the characteristics of slug flow at high water superficial velocity (J_L=1.59 m/s). As explained earlier, slugs formed at high water superficial velocity would quickly reach a constant slug length at the same nose and tail velocities. Meanwhile, at high air superficial velocity (J_G=3.35 m/s), several irregular waves were formed in the fully developed flow test section area. In addition, at high J_G and J_L, the level of interference at the flow interface highly influenced the effect of surface tension of flow interface. It was therefore the top of the pipe could not be covered by liquid and the arise waves as the disturbance in the inlet dominantly cause break up in the waves as shown in Figure 11.

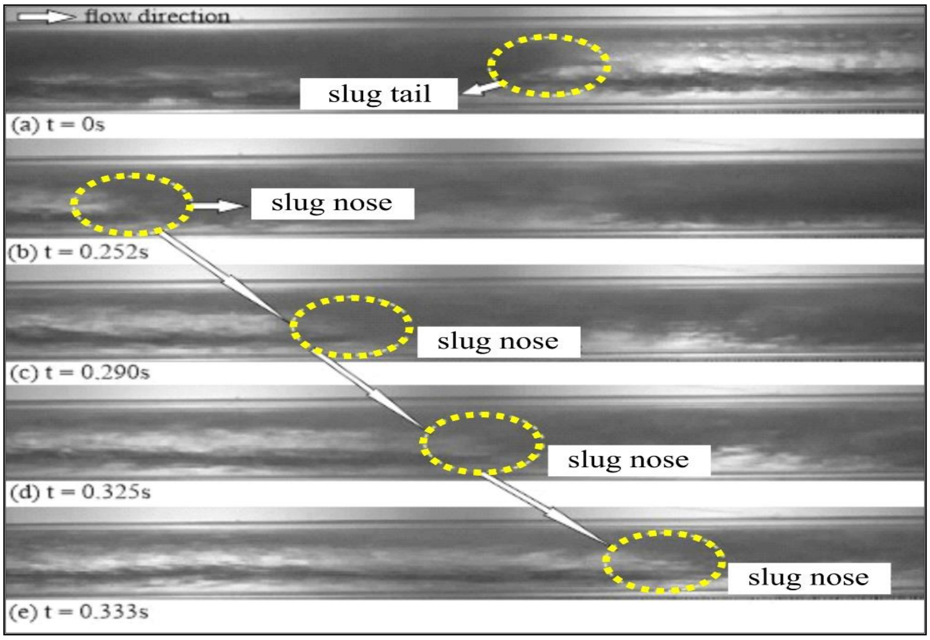

Fig. 10. Visualization of fully developed slug flow at 200D at J_G=2.65 m/s and J_L=1.59 m/s

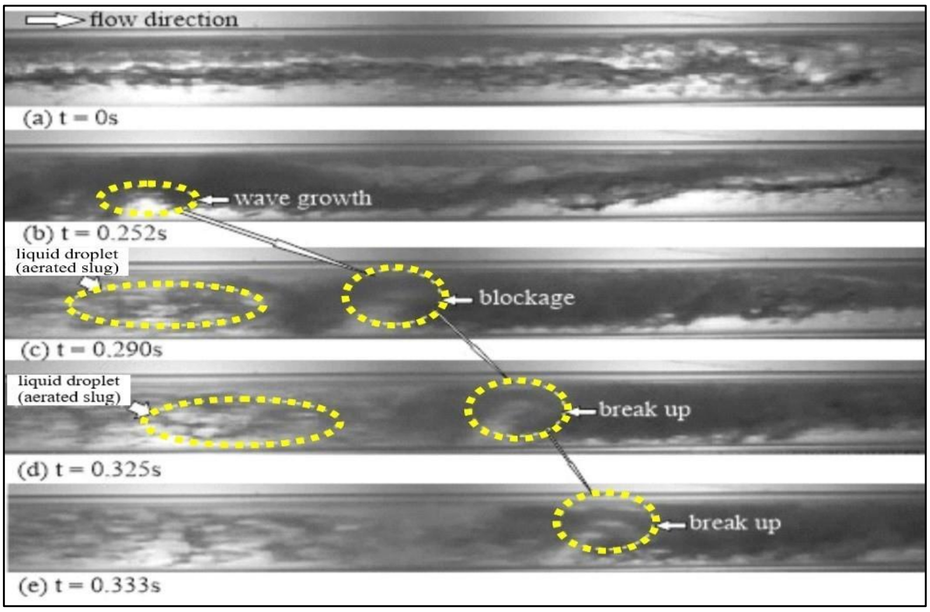

Fig. 11. Visualization of fully developed slug flow at 200D at J_G=3.35 m/s and J_L=1.59 m/s

3.2 Slug Flow Development Characteristics
3.2.1 Void fraction

Figure 12 reveals the effect of air superficial velocity on void fraction. It can be seen that higher air superficial velocity resulted in the higher void fraction. Naturally it happened in the formation of liquid film in the pipe surface. During the improvement of air superficial velocity, liquid area in slug flow pattern was rapidly get rid of by gas, thus indirectly increase void fraction.

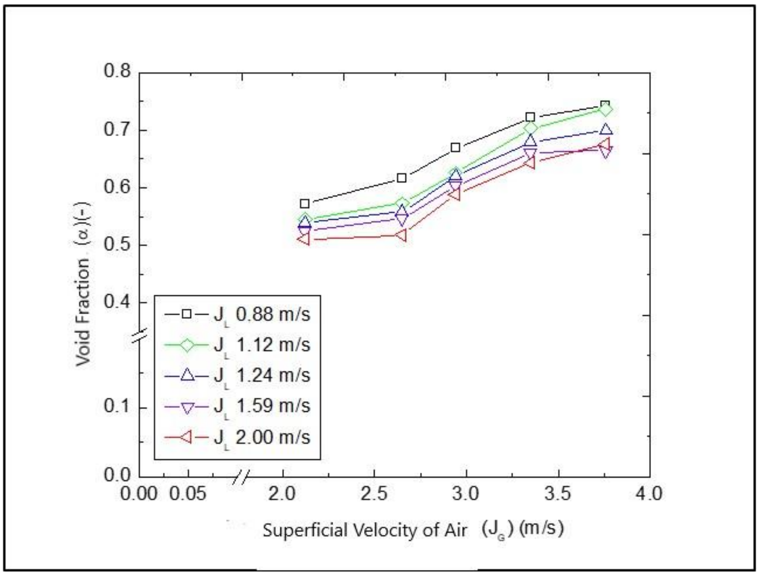

Fig. 12. Effect of air superficial velocity on void fraction at various water superficial velocity

Slug flow occurred due to the increase of gas velocity and flow blockage followed by bubbles at high velocity of sequential slug flow to gas velocity. Theoretically, void fraction could be determined using two approaches. These approaches are called homogeneous flow model and separated flow model as proposed by Wallis [21]. Void fraction of a homogeneous flow model is determined as follow

$$x = \frac{\dot{m}_G}{\dot{m}_G+\dot{m}_L} = \frac{G_G}{G_G+G_L} \tag{3}$$

$$\alpha = \frac{Q_G}{Q_G+Q_L} = \frac{J_G}{J_G+J_L} \tag{4}$$

whereas void fraction of separated flow model is determined using the following equation

$$\alpha = \frac{\phi_l - 1}{\phi_l} \tag{5}$$

Another void fraction estimation has also been reported by Bonnecaze *et al.,* [22] based on the experimental data conducted in a horizontal pipe of 1.5-inch internal diameter and 80 ft length with inclination of -10° to 10° as the following equation

$$\alpha = \frac{J_G}{C_o(J_G+J_l)+u_{BR}} \tag{6}$$

$$u_{BR} = 0.35\sqrt{gd\left(1-\frac{\rho_G}{\rho_L}\right)} \tag{7}$$

Figure 13 shows a comparison of measured void fraction to predicted void fraction proposed by Wallis [21] and Bonnecaze *et al.,* [22] at a constant water superficial velocity of 0.88 m/s. As shown, the measured void fractions provided good agreement to all predicted void fraction models within ±30% error band.

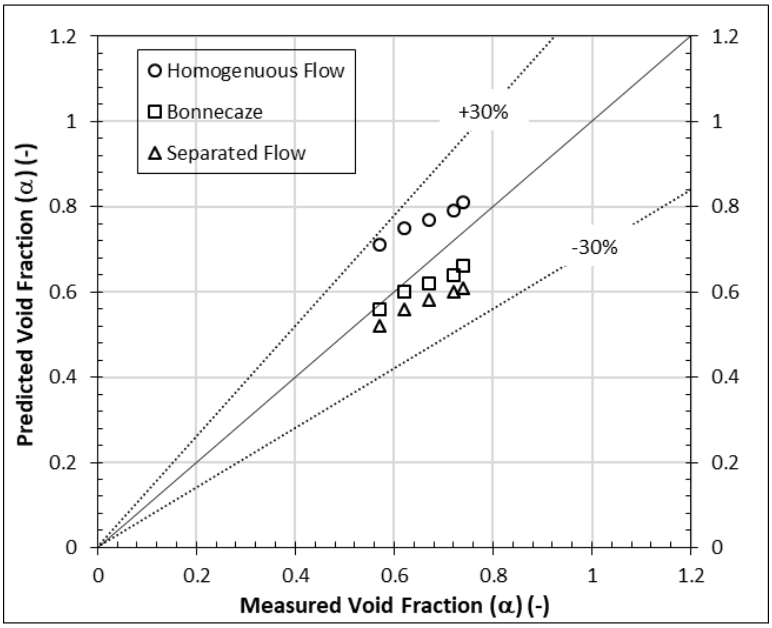

Fig. 13. Predicted against measured void fractions (J_G = 2.12 – 3.78 m/s and J_L = 0.88 m/s)

The overall mean absolute error was 12.01% only. Meanwhile, the best fit of measured data was obtain with the predicted model proposed by Bonnecaze *et al.,* [22] with average mean absolute error of below 7%. This emphasize that the measured void fraction has a considerably good result in the determination of void fraction.

3.2.2 Pressure drops

In complex condition, complicated analysis is not needed to determine pressure drop. In this work, pressure drops occurred in the pipe were evaluated based on adiabatically pressure drop of two phases flow given by Lockhart and Martinelli [23], generally called Lockhart-Martinelli parameter. The evaluation was also supported with correlation recommended by Chisholm [24] by incorporating Chisholm coefficient for various types of flow. The use of this approach has been proven and recommended by Naidek *et al.,* [25] who expanded the correlation application for corrugated pipes. The adiabatically pressure drop of two phases flow could be determined using the following equation

$$\left(\frac{dp}{dx}\right)_M = L_2^{\emptyset}\left(\frac{dp}{dx}\right)_L = G_2^{\emptyset}\left(\frac{dp}{dx}\right)_G \tag{8}$$

in which pressure gradient for each fluid is

$$\left(\frac{dp}{dx}\right)_L = \frac{4\,f_wL}{D}\frac{\rho_L {J_L}^2}{2} \tag{9}$$

$$\left(\frac{dp}{dx}\right)_G = \frac{4\,f_wG}{D}\frac{\rho_G {J_G}^2}{2} \tag{10}$$

while friction force to the wall of each fluid is

$$f_wL = \frac{16}{Re_L} \text{ at } Re_L = \frac{\rho_L J_L D}{\mu_L} < 2000 \tag{11}$$

$$f_wL = 0.046\ Re_L - 0.2 \text{ at } Re_L = \frac{\rho_L J_L D}{\mu_L} \geq 2000 \tag{12}$$

$$f_wG = \frac{16}{Re_G} \text{ at } Re_G = \frac{\rho_G J_L D}{\mu_G} < 2000 \tag{13}$$

$$f_wG = 0.046\ Re_G - 0.2 \text{ at } Re_G = \frac{\rho_G J_L D}{\mu_G} \geq 2000 \tag{14}$$

$L_2^{\emptyset}$ and $G_2^{\emptyset}$ given in the function of $x_{Lock-Mart}$ which is defined as

$$x_{Lock-Mart} = \left[\frac{\left(\frac{dp}{dx}\right)_L}{\left(\frac{dp}{dx}\right)_G}\right]^{\frac{1}{2}} \tag{15}$$

Chisholm [24] gave the equation

$$L_2^{\emptyset} = 1 + \frac{C_{chis}}{x_{Lock-Mart}} + \frac{1}{Lock-Mart_2^X} \quad (16)$$

$$G_2^{\emptyset} = 1 + C_{chis}.x_{Lock-Mart} + Lock - Mart_2^X \quad (17)$$

Each flow type has C_{Chis} as shown in Table 1.

Table 1
Chisholm Coefficient

Gas	Water	C_{Chis}
Laminar	Laminar	5
Laminar	Turbulent	10
Turbulent	Laminar	12
Turbulent	Turbulent	20

The effect of air superficial velocity on the pressure drop is given in Figure 14. The increase of pressure drops due to variation of air superficial velocity occurred because the increase of air superficial velocity forced liquid slug (L_S) to quickly moved. Continues increment of air velocity that lead to the change of flow pattern resulted to the replacement of liquid area by gas and the pressure drop would be constant. The excessive increment of air superficial velocity thus lead to turbulent water flow would re-increase pressure drop according to the friction force.

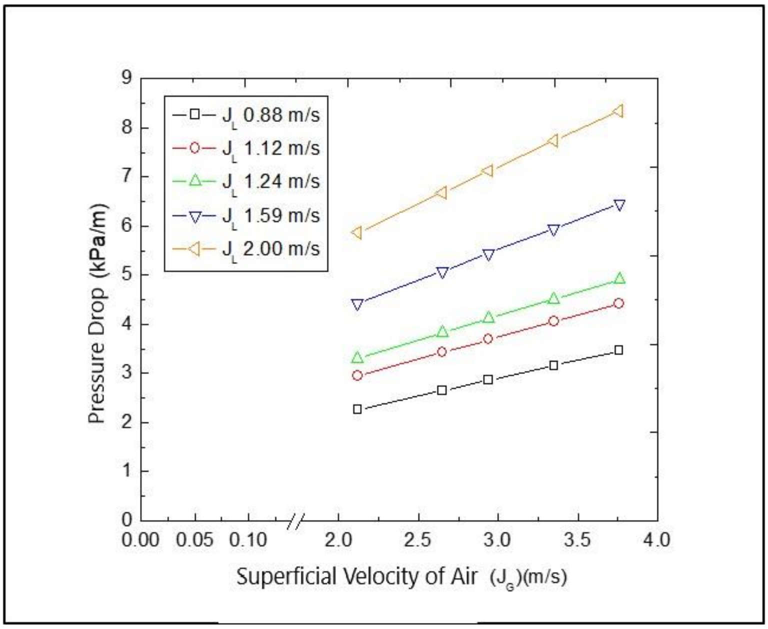

Fig. 14. Effect of air superficial velocity on the pressure drop at various water superficial velocity

Figure 14 also shows that changes in water superficial velocity also affect the pressure drop in the pipe. The pressure drop increases significantly with the increase of water superficial velocity. This is caused by the high fluid friction intensity and permeability due to the increment of water amount entering into the pipe, leading to high fluid instability [26]. This result implies that high pressure drop of slug flow is the reason of anticipating slug flow in horizontal hydraulic pipe.

3.2.3 Slug frequency

Figure 15 shows that the decrease of slug frequency by the addition of air superficial velocity at constant water superficial velocity occurred due to the increase of gas flow into the pipe. Because of the fixed cross-sectional area of the test section pipe, the increase of gas flow forced a portion of the liquid bag, therefore to equalize the mass of gas entering in the test section pipe, the air bag become longer, resulted in longer reading interval of slug liquid. During the observation of frequency data at slug development area at 200D, it was found that slug frequency tended to decrease as the increase of air superficial velocity at constant water superficial velocity.

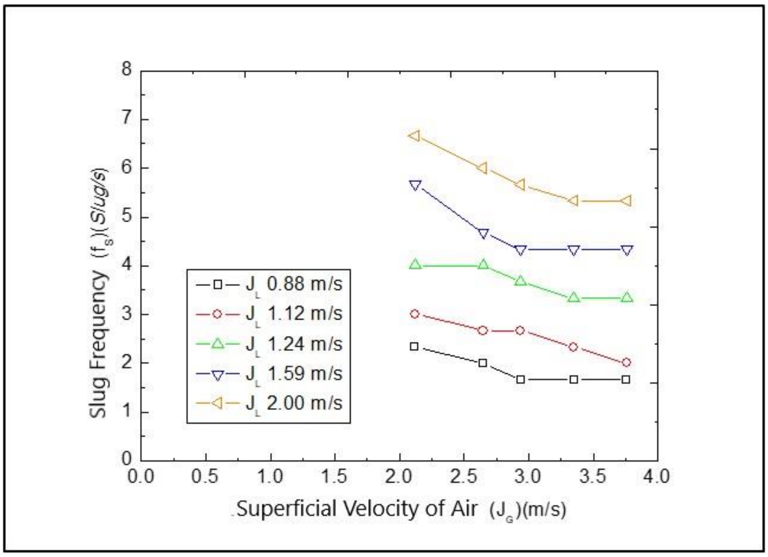

Fig. 15. Effect of air superficial velocity on the slug frequency at various water superficial velocity

Figure 15 also shows that slug frequency became higher by the increase of water superficial velocity due to the increment of water amount entering into the test section. To equalize the addition of water mass in the cross section of test section, the frequency of the slug liquid will increase so that the liquid flow in the pipe will move faster and directly affect the amount of liquid slug that appears in the observed test section.

Besides being visually observed as given in the above discussion, slug frequency prediction can also be done using equations obtained from several researchers including Gregory and Scott [27], Greskovich and Shrier [28], and Heywood and Richardson [29]. Gregory and Scott [27] recommended the following equation to calculate slug frequency for carbon dioxide fluid and water in pipes of 1.9 cm in diameter

$$f_s = 0{,}0226[\frac{J_L}{gD}\left(\frac{19{,}75}{J_M} + J_M\right)]^{1{,}2} \tag{18}$$

Greskovich and Shrier [28] applied their data to define slug frequency along the pipe

$$f_s = 0{,}0226[\lambda\left(\frac{2{,}02}{D} + \frac{{J_M}^2}{gD}\right)]^{1{,}2} \tag{19}$$

where λ refers to water volumetric quality, in which $\lambda = J_L/J_M$.

Heywood and Richardson [29] provided the following equation for slug frequency

$$f_s = 0{,}0434[\lambda\left(\frac{2{,}02}{D} + \frac{{J_M}^2}{gD}\right)]^{1{,}02} \quad (20)$$

These theoretically obtained slug frequencies were then plotted for comparison purposes with the obtained result in the current study as presented in Figure 16.

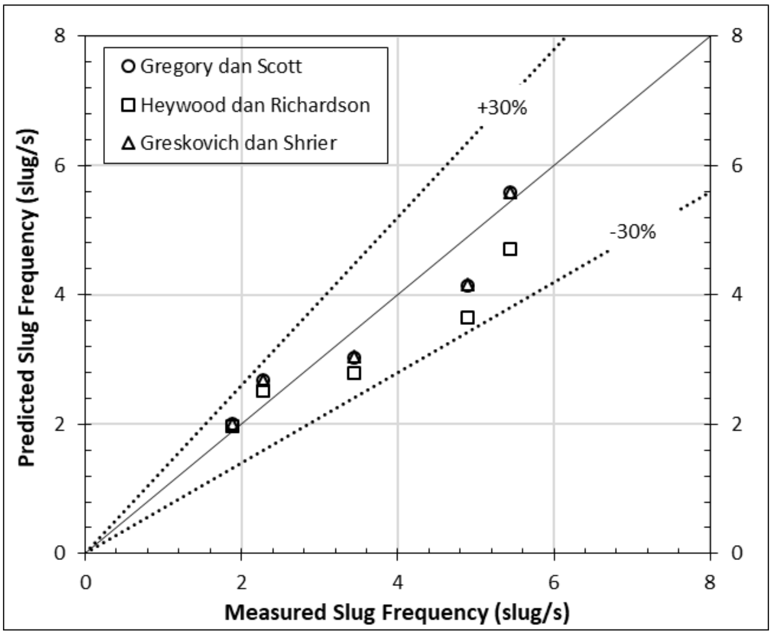

Fig. 16. Predicted against measured slug frequencies (J_G = 3.76 m/s and J_L = 0.88 – 2 m/s)

Figure 16 compares the slug frequency predicted by the correlation with measured data at a constant air superficial velocity of 3.76 m/s. It is shown that all data lie within ±30% error range. The overall mean absolute error was found to be 11.97% only. In addition, the measured slug frequencies provided better agreement to predicted correlation proposed by Gregory and Scott [27] with average mean absolute error of about 10.70%. This emphasize that the measured slug frequency has a considerably good result in the determination of slug frequency under the investigated condition. This result is important for complementing slug frequency base data. Hernandez-Perez *et al.,* [30] described that slug frequency is a complicated parameter that need to be considered in data processing.

3.2.4 Liquid slug velocity

Figure 17 indicates that average liquid slug velocity increased with the increase of air superficial velocity. It happened due to the incorporation of liquid bag with dispersed gas or the aeration of observed flow system. Initially, in horizontal pipe, liquid phase was available in the bottom of pipe cross section and the gas phase was separately available on the top. This is due to gas density was lower than water density. Along with the increase of gas superficial velocity and due to the gas phase, which was originally available as air bag finally has superficial velocity that is higher than the liquid superficial velocity. The air bag pushed the liquid slug occupied pipe cross section. Due to the excessive gas superficial velocity above the liquid bag limit, some of the air bag incorporated with liquid and air bags entering the fluids and underwent air dispersion or aeration.

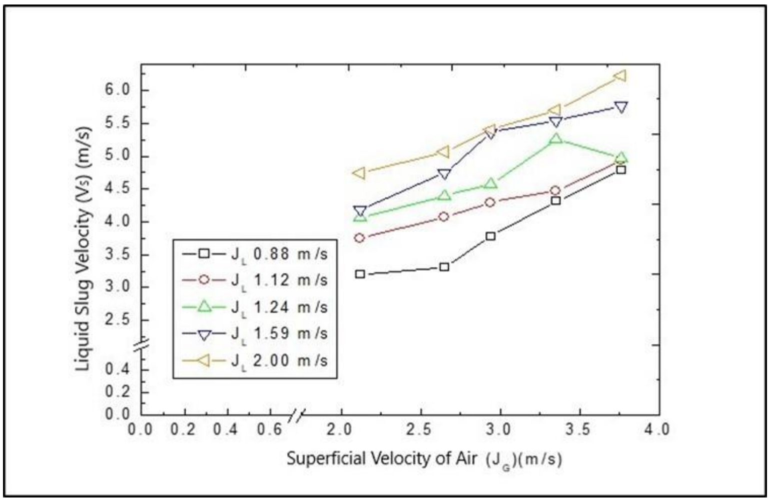

Fig. 17. Effect of air superficial velocity on the average liquid slug velocity (V_S) at various water superficial velocity

The air dispersion carried liquid bag moving faster. Moreover, direction of gas and liquid flows moved in the same direction caused each phase pushing lower velocity phase. As a result, the formed slug flow was faster than gas superficial velocity and liquid superficial velocity. The previous studies conducted by Wang *et al.,* [31] and Mohmmed *et al.,* [32] found that the movement of liquid slug in horizontal pipes resulted in the increment of liquid slug velocity as the increase of gas superficial velocity and liquid superficial velocity. The similar trends of the liquid slug velocity were also observed based on the data analysis carried out in this work.

4. Conclusions

The effect of fluids superficial velocity on the characteristics of slug flow in a horizontal hydraulics pipe was successfully investigated. Slug flow characteristics changed according to the fluid superficial velocity variations. Although the change of fluid superficial velocity values was small, it was able to provide complex flow characteristics. Several mechanisms of slug flow initiation were observed. At low to medium J_G with low to high J_L, slug flow initiation mechanisms consisted of wave growth, hydraulic jump, blockage, and slug decaying. While at medium to high J_G with low to high J_L, wave initiation, wave formation, disturbance, wave coalescence, and incompletely developed slug mechanisms were found. For fully developed flow cases observed at 200D, the results showed that void fraction of the slug flow increased considerably with the increase of J_G, whereas the increase of slug frequency was more influenced by the increase of J_L. Meanwhile, pressure drop and liquid slug velocity changed dramatically with the change of both J_G and J_L. This information is important for designing fluid flow in small horizontal hydraulics pipes in order to avoid the impact of slug flow in industrial applications.

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