Experimental Study On The Interfacial Behavior Of Air-Water Plug Two-Phase Flow In A Horizontal Pipe

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Abstract: When gas flows over a liquid surface with a large slip velocity in horizontal pipes, t he interface can become disturbed and large amplitude waves are generated. If the amplitude of these waves is large enough, therefore, it will blocks the cross sectional area of the pipelines. Understanding of this flow pattern is essential in addressing key operational and safety issues relating to the pipeline operation both off and on shores. The interfacial behaviors of air-water slug two-phase flow in a horizontal pipe have been investigated experimentally. Experiments were carried out at atmospheric pressure and the effects of superficial liquid and gas velocities were investigated. The test section used for the experiments is 9.5 m in length, with an internal diameter of 16 mm. A constant electric current method (CECM) and visual observation were utilized to elucidate the initiation and the subsequent evolution of hydrodynamic slugs in a horizontal pipeline. The measured data were processed to obtain the information of the axial distribution of gas void fraction data, statistical distributions of slug lengths and of the time intervals between slug arrivals. Those data reveals the influence of the liquid flow field development on the interfacial structure. In particular, the new data of axial void fraction profiles and interfacial characteristics suggest that the slug flow development is strongly affected by the liquid flow structure. Next the data are used also to examine the accuracy of available correlations in open literature to predict the slug flow behavior in a horizontal pipe.
Key Words: Slug flow, Horizontal pipe, Instantaneous gas void fraction, Slug length, Wave velocity

1. Introduction

Plug or slug flow has been studied in addressing key operational and safety issues relating to offshore development. It can be categories into two main groups: hydrodynamic and terrain slugging. Terrain slugging is characterized visually as a liquid accumulation in local dips of flow lines with variable topography. Those are liquid and gas slugs that are appeared randomly. Once formed, liquid slug initially grow in length, with their fronts traveling faster than their tails (Ujang et al., 2006). The occurrence of random liquid and gas slugs will produce a high fluctuation of the transient pressure gradient in the pipe. Therefore, it will influence the performance of the supporting equipment in their operation such as injection pump and piping system its self.

Plug or slug formation in a co-current two-phase in a horizontal pipe has been studied so far in order to know the responsible mechanism of the plug development in the pipe [King et al., (1998), Teyssedou and Tye (1999), Woods et al., (2006), and Ujang et al., (2006)]. For all those studies, however, the obtained basic mechanisms are still unclear, whereas there is few systematical data to support the proposed slug mechanisms. Therefore, the fundamental data on their topology including liquid and gas slugs length, the propagation velocity, and slug frequency are needed.

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One of the shortcomings of proposed slug development mechanisms is the fact that the slug flow is determined subjectively. That is identification of onset of flooding was often made, for example, by using visual observation or recorded video images, and this may account for large discrepancies among reported experimental data. The purpose of the present experiment was to use the instantaneous liquid hold-up data, which were measured at three axially different locations, each 215 mm apart along a horizontal pipe, in order to investigate the basic topologies during the occurrence of plug/ slug flow. In this experiment, a constant electric current method (CECM) was applied to detect the instantaneous liquid hold-up in adiabatic air-water plug co-current two-phase flow. This method is capable of making measurements with satisfactory accuracy, even when the liquid film thickness is very thin because the output signal becomes large as the film thickness decreases. It was originally developed by Fukano (1998) to observe the interfacial structure in co-current gas liquid two-phase upward flow. Recently, it was used by Deendarlianto et al. (2010) to study the effect of liquid surface tension on the counter-current flow limitation in gas-liquid two-phase flow in an inclined pipe.

In the present report, the experimental results of instantaneous liquid hold-up combined with the visual observation results of the plug flow will be presented first. These data will be explained in terms of wave growth and propagation of the flow. Next, the effects of the superficial velocities of liquid and gas on the flow topologies of plug flow will be discussed briefly. Finally, the wave velocity and wave frequency during the plug flow will be evaluated. The obtained experimental data will be discussed with reference to proposal reported by other investigators

2. Experimental Apparatus and Procedures

The experiments were conducted in horizontal two-phase flow test facility at the Fluid Dynamic Laboratory, Department of Mechanical & Industrial Engineering, Gadjah Mada University. The test facility allows air-water experiment at room temperature and can be operated from stratified until annular flow as shown in Figure 1. As shown in the Figure1, a test section of horizontal pipe of 16.0 mm in inner diameter (D), 9.5 m in total length, and made of transparent acrylic resin was used to observe the flow phenomena. From the figure, air from compressor entered from the air inlet of the pipe and flowed through the test section to a separator. Meanwhile, water measured by a flow meter, entered from the water inlet and flow concurrently with the air in the pipe. To ensure the accuracy, the liquid flow rate was confirmed by collecting the liquid discharged from the lower outlet of test pipe, in a measuring cylinder over a fixed period of time.

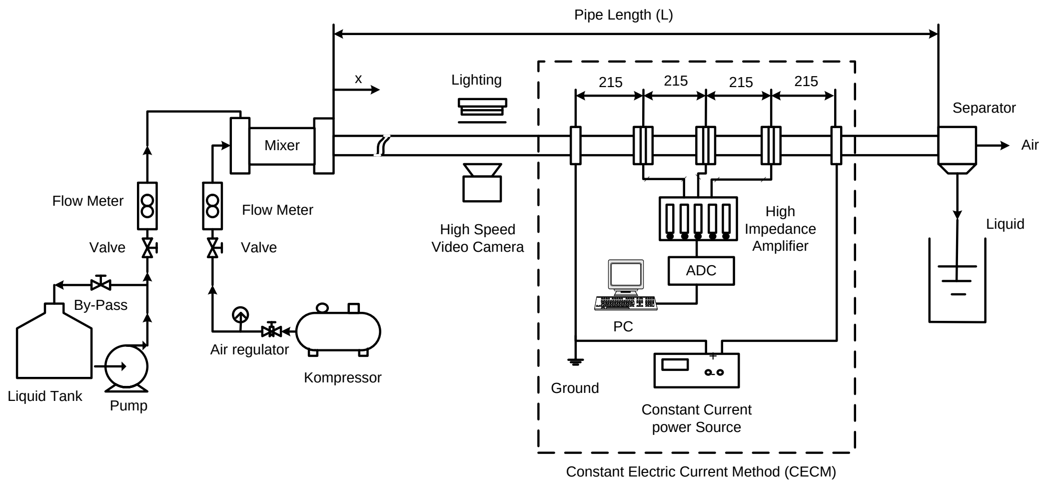

Figure 1. Schematic diagram of experimental apparatus

In the present experimental works, the flow behavior was investigated by measuring the instantaneous local liquid hold-up by using CECM shown also in Figure 1. Here we used three pairs of liquid hold-up sensors arranged with an axial spacing of 215 mm. Each sensor consists of a pair of brass electrodes, 1 mm in thickness, 5 mm apart from each other, mounted flush with the inner surface of the test pipe. The output signals from these sensors were sent respectively through the floating amplifier with high input impedance to a personal computer via an A/D converter. In this experiment, the sampling rate was 1.0 kHz for each experimental run. The details of the experimental apparatus, principle and calibration method can be found in Fukano (1998).

In order to verify the liquid film behavior recorded on a personal computer by using CECM, visual observations were performed by using two CCD cameras positioned 7 m from the the water and air inlets. The shutter speed was 1/10,000 s. The experimental conditions were as follows; the range of water superficial velocity: J_L=0.16~1.13 m/s, and that of air; J_G=0.12~1.88 m/s. Working fluids: air and water. Water temperature was approximately 25° C. The range of flow condition studied is shown in Figure 2. It is noted that the data were taken from plug to slug flow. The data at the transition flow pattern was also taken. In addition, the observed flow pattern is compared with those of Weismann et al. (1978), Taitel & Dukler (1976), and Mandhane et al. (1974). The result indicated that the observed flow patterns are in agreement with the proposed flow pattern from Mandhane et al.

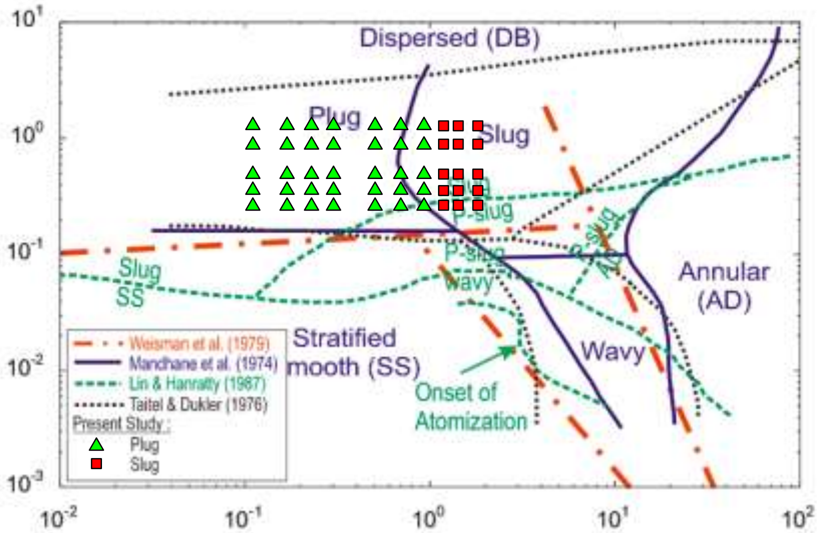

Figure 2. Experimental range

3. Result and Discussion

Figure 3 shows the example of interfacial behavior, time variation of liquid hold-up, and its probability distribution function (PDF) of plug flow. The liquid superficial velocity was 0.31 m/s as an example. In the figure, (a), (b), (c) corresponds to the cases of gas superficial velocity of 0.18 m/s, 0.70 m/s, and 1.57 m/s respectively. Typical photographs, time variation of liquid hold-up, and its probability distribution function of this flow pattern are shown in Figures 3(1), 3(2) and 3(3), respectively. As shown in Figure 3, this flow pattern is characterized by liquid slug of various lengths separated by gas slug, depending on the gas superficial velocity. Close observation of the photographs revealed that the tiny bubble around the nose of air slug increase as the gas superficial velocity increases (as the flow transit from plug to slug flow). Next, the liquid hold-up signals fluctuate periodically showing low and

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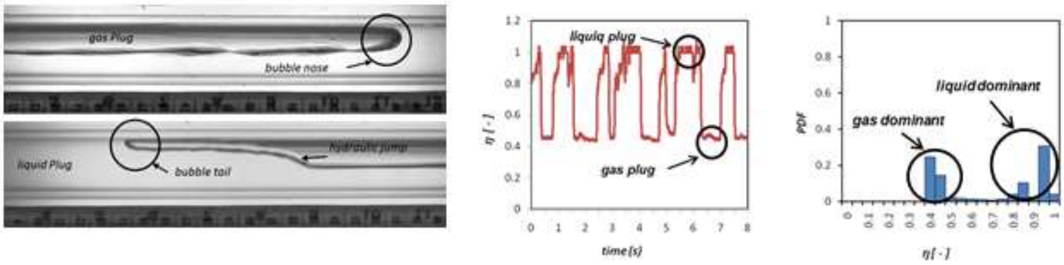
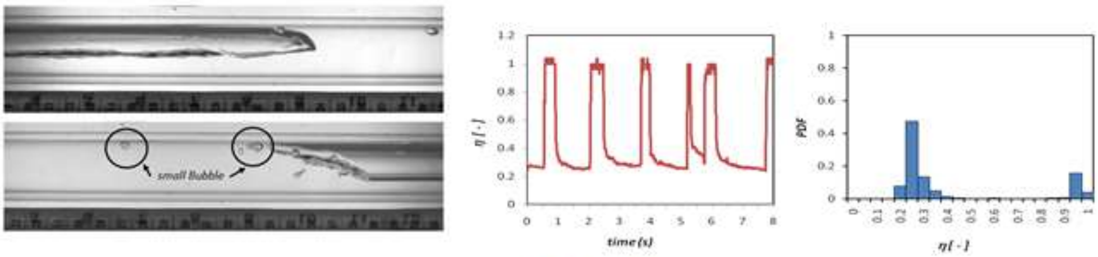
high η values, which depend on the passing of liquid and gas slugs. The output signals of liquid hold-up fluctuate strongly as the appearance of tiny bubbles. In addition, the liquid film blocks the pipe to prevent the gas slug passes the motion of liquid slug.

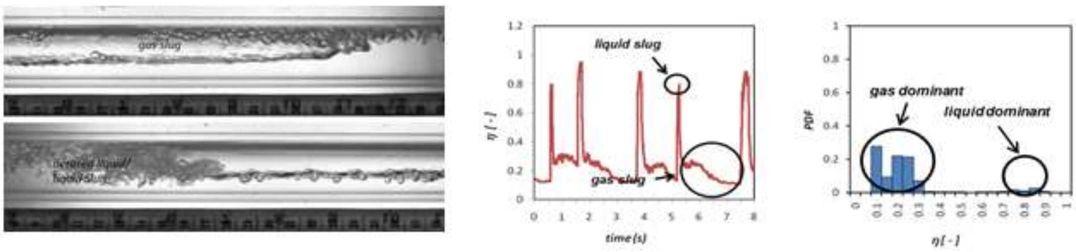
Figure 3 shows also that the gas-liquid interfacial structures strongly depend on the superficial gas velocity, whereas the number of small bubble increases as superficial gas velocities increases, and the interface appears to be chaotic. Next, the distribution of PDF data has twin peaks, indicating the liquid hold-up values of liquid or gas dominant. As the superficial gas velocity increases the peak move from liquid to gas dominant indicating that flow patterns change from plug to slug flow. The observed phenomena were also similar to that of Costigan & Whalley (1997) who conductec the slug flow idenfication of gas-liquid in vertical pipe



(a) J_G= 0.18 m/s



(b) J_G= 0.70 m/s



(1) J_G= 1.57 m/s

Figure 3. Examples of interfacial behavior, liquid

(1)Visual observation; (2) Liquid hold-up; (3) PDF hold-up, and probability distribution function (PDF) of Plug Flow (J_L=0.31 m/s)

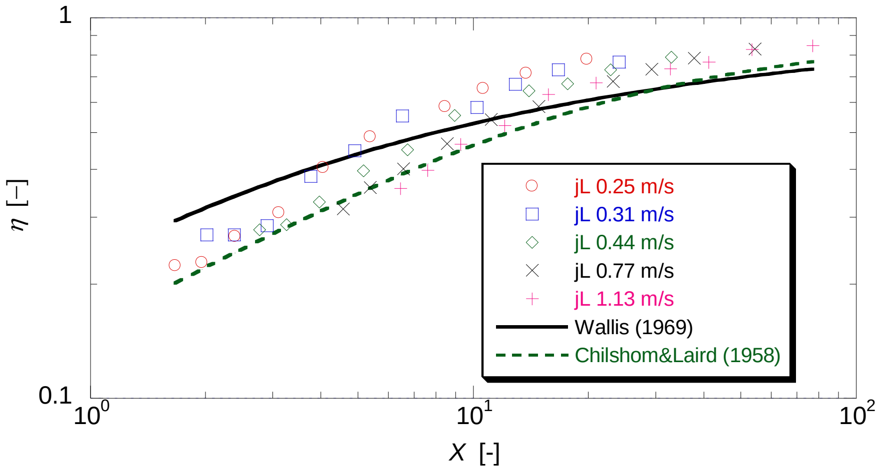


Figure 4. Relationship between the Martinelli parameter and averaged liquid hold-up.

Figure 4 shows the relationship between averaged liquid hold-up, η, and Martinelli parameter, X, obtained in the present experimental study. For the comparison, the correlations proposed by Chilshom & Laird (1958) and Wallis (1969) are plotted in the figure. Close observation of the figure indicated that under a constant liquid superficial velocity, the liquid hold-up increases as the increase of Martinelli parameter. Next, the measured averaged liquid hold-up data of plug/ slug flow are distributed the area or Chilshom & Laird and Wallis curves at low Martinelli parameter. Meanwhile those correlations are under predicts to the data at a higher Martinelli parameters.

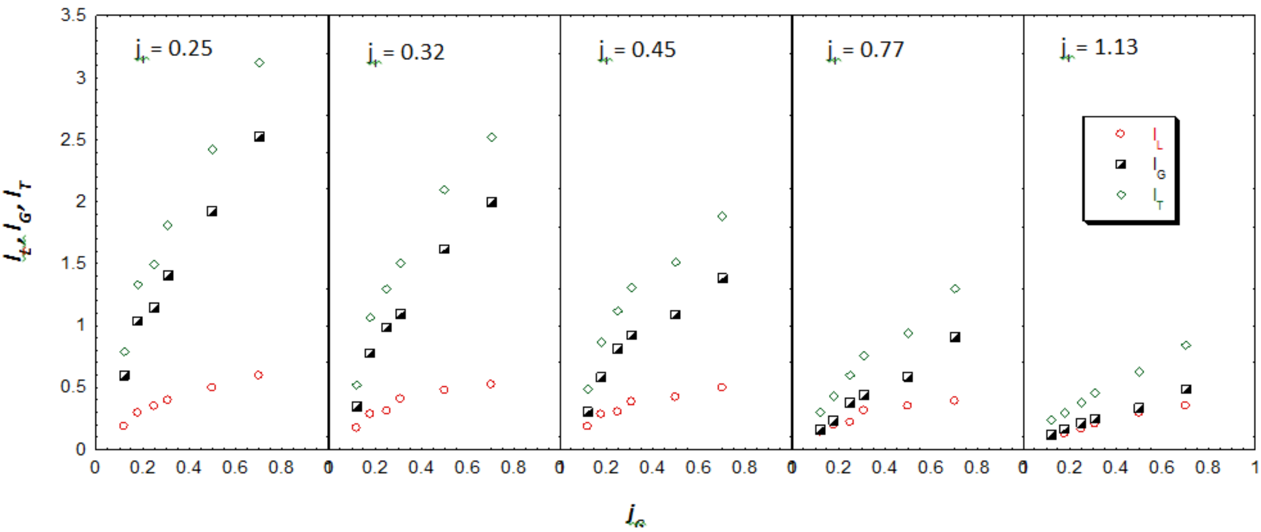


Figure 5. The effect of superficial gas velocities on the air, water and total slug lengths

Figure 5 shows the effect of the gas superficial velocity on the length of liquid and gas slugs obtained from the experimental study. As shown in this figure, the length of gas slug (I_G) and the length of liquid slug (I_G) depended strongly on the gas and liquid superficial velocities. I_G and I_L increase with the increase of superficial gas velocity, and decreases as the gas superficial velocity increases. The length of gas slug is higher than that of liquid in any experimental conditions. The observed phenomena agree well to that of Ousaka et al. (1999) who examined the effect of air-water mixing method on behaviour of air slug in inclined upward flow. This fact indicated also that the inclination angle does not affect the phenomena.

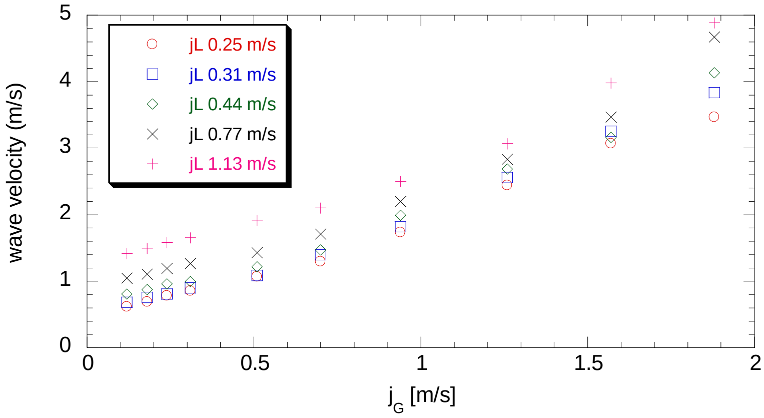


Figure 6. Velocity of nose air slug

Figure 6 shows the effect of superficial gas velocity on the velocity of nose air slug. The velocity of nose air slug was determined from the delay time of a maximum peak in the cross-correlation function between any two signals by the CECM located at three different locations with each separation of 215 mm. The velocity obtained from CECM was compared with the analyzing of successive frame obtained by using a high-speed video camera. From the results shown in Figure 6 it is revealed that velocity of air slug increases as both the superficial velocities of liquid and gas. The increase becomes larger as the liquid superficial velocity increases.

Figure 7 shows the variation of the air slug frequency plotted as a function of liquid and gas superficial velocities. It was determined by counting the number of slug from the traces of the time variation of liquid hold-up. It was also checked by the wave frequency as observed on the video recording. As can be seen in Figure 7, the air slug frequency increases with the increase of liquid superficial velocity. On the other hand it independents from the gas superficial velocity. The reasons for this effect are not fully understood, but it probably occurs because of the change in the liquid film distribution and the occurrence of tiny bubble as the flow pattern change from plug to slug flow. Therefore a further observation on this topic is needed in the future.

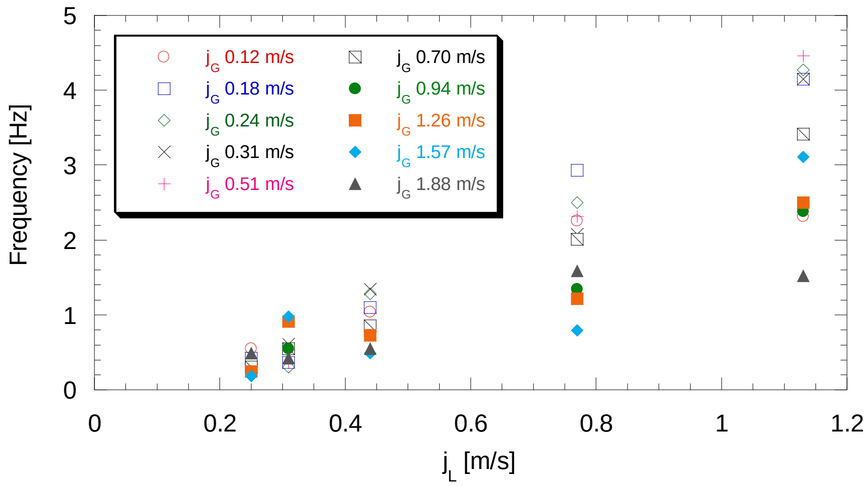


Figure 7. Air slug frequency

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4. Conclusion

The interfacial behaviors of air-water slug co-current flow in a horizontal pipe were investigated experimentally. The inner pipe diameter and the pipe length were respectively 16 mm and 9.5 m, respectively. The results are summarized as follows:

(1) The superficial gas velocity significantly affects the time variation of liquid hold-up in the plug flow, i.e., it fluctuates strongly with increasing gas superficial velocity. The strong fluctuation is affected due to the appearing of tiny bubble in the gas phase. This fact indicates that the liquid transportation mechanism in plug flow changes with increasing the gas superficial velocity.

(2) In all the experimental range, the length of gas slug is higher than that of liquid. The length of both of air or liquid slug increases with the increase of gas and liquid superficial velocities.

(3) From the nose slug velocity and passing air slug frequency, it was found that the liquid superficial velocity has a significant effect on them. That is the nose slug velocity and passing air slug frequency increase as the liquid superficial velocity increases.

5. Nomenclatures

J : Superficial velocity (m/s)

X : Martinelli parameter (-)

PDF : Probability distribution function (-)

Greek letters

η : Liquid hold-up (-)

Subsripts

G : Gas

L : Liquid

T : Total

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