Statistical Analysis of the Effect of Reduced Surface Tension on Horizontal Annular Flow: Probability Distribution Function of Liquid Holdup

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ABSTRACT

A research on gas-liquid horizontal annular flow has been conducted in 16 mm pipe using gas and liquid superficial velocity of 12 to 40 m/s and 0.05 to 0.2 m/s with liquid surface tension of 71, 40, and 38 mN/m. To investigate the characteristics of liquid holdup, the probability distribution function (PDF) of liquid holdup signal has been analyzed. The liquid holdup decreases when the gas superficial velocity increases and the surface tension decreases. From PDF analysis, it is noticed that the fluctuation of liquid holdup is high when the gas superficial velocity is low and liquid superficial velocity is high.

Keywords:
Horizontal annular flow, liquid holdup, surface tension, probability distribution function

1. INTRODUCTION

Study of gas-liquid two-phase annular flow has been conducted extensively for decades to investigate the characteristics of such flow. Models for annular flow have also been developed. However, the models for horizontal floware less successful than those of vertical flow due to the high uncertainty. As a result, many important questions remain unanswered [1]. For the flow mechanism, only few investigations have been done and even the fundamental data is still lacking [2]. The mechanism by which the liquid film is formed at the inner surface of pipe wall, especially in the upper part, are not yet agreed by the researcher in two-phase flow discipline.

In two-phase flow, two parameters are commonly used, liquid holdup and void fraction. Both parameters are important in characterizing two-phase flow, such as the two-phase density, two-phase viscosity, average velocity, flow transition, pressure drop, and heat transfer. *Liquid holdup*, or liquid fraction, is defined as the fraction of an element of pipe which is occupied by liquid [3], or

$$\eta = \frac{A_L}{A} \quad (1)$$

On the other hand, *void fraction* is defined as the fraction of an element of pipe which is occupied by gas, or

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

where$A$ is the pipe cross sectional area, $A_L$is the cross sectional area occupied by liquid, and $A_G$is the cross sectional area occupied by gas.

As $A_L + A_G = A$,then the expression for liquid holdup and void fraction could be written as

$$\eta = \frac{A_L}{A} = \frac{A - A_G}{A} = 1 - \alpha \quad (3)$$

Statistical analysis is one of popular method in investigating the annular two-phase flow. The probability distribution function (PDF) has been used by [4,5,6,7].

Surface tension has an important role in two-phase flow. It affects many parameters in such flow: liquid holdup, film thickness, entrainment rate, wave velocity, wave amplitude, and wave frequency. Extensive studies on the effect of surface tension on two-phase flow have been conducted by [8,9,10,11,12,13].

Due to the importance of the effect of surface tension and distribution function of liquid holdup, this paper is aimed to contribute the data bank of two-phase flow, especially for the case of flow with different liquid surface tension. In this paper, the statistical analysis using probability distribution function of liquid holdup is discussed. The effect of flow condition on the liquid holdup is examined based on the statistical point of view. In addition, the effects of the reduced surface tension on the liquid holdup in various liquid and gas superficial velocityare also explored.

2. EXPERIMENTAL SETUP

The experiment was conducted at Fluid Mechanics Laboratory, GadjahMada University, using an experimental rig as shown in Figure 1.

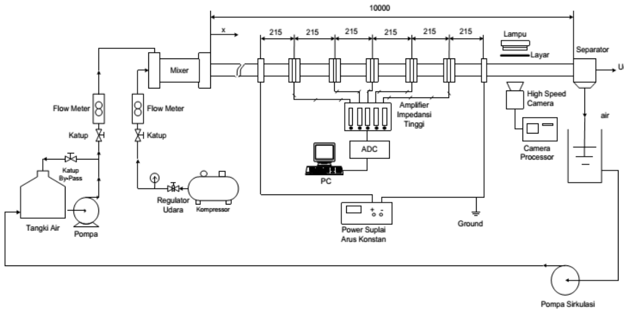

Figure 1.Experimental rig.

The test section is acrylic resin tube with an inner diameter of 16 mm. Air enters at the pipeline from a compressed air supply and water is injected through a porous mixer to reduce the development length. The test section is located at a distance of more than 200 tube diameter to guarantee that the flow is fully developed. In view of the fact that water entered through a porous medium, it is ensured that the length is sufficient for the flow to befully developed. The detailed experimental rig could be found in [13].

To investigate the effect of surface tension, three different values of liquid surface tension were used in this experiment. The first is water with a surface tension of 71 mN/m (denoted as W71). The surface tension is then reduced using butanol as a surfactant. Using 2% butanol solution, the surface tension is reduced to 40 mN/m (denoted as S40). Addition of the concentration of butanol to 5% gives the surface tension of 38 mN/m (denoted by S38).

To investigate the liquid holdup in annular flow, the gas and liquid superficial velocity are set to 12 to 40 m/s and 0.05 to 0.2 m/s, respectively. The test matrix in the Mandhane map [15] is presented in Figure 2.

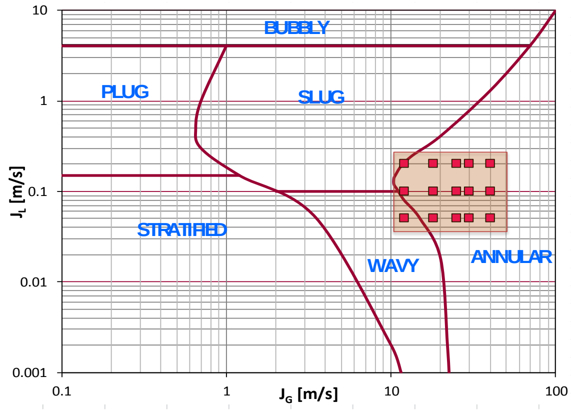

Figure 2.Experimental matrix.

3. RESULTS AND DISCUSSION

The liquid holdup for each combination of liquid and gas superficial velocities are measured using a sampling rate of 500 Hz and 30 s data recording. The typical traces of liquid holdup signals for experiment with different liquid surface tensionare presented in Figure 3.

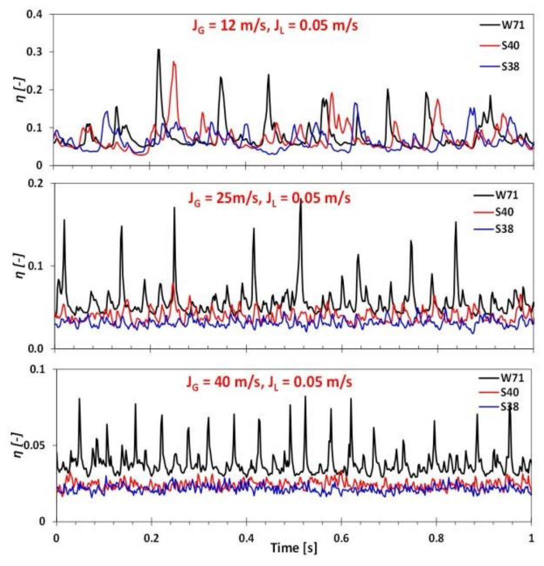

Figure 3.Effect of J_G and surface tension on the liquid holdup (J_G is varied from 12 to 40 m/s and J_L constant = 0.05 m/s).

For the lowest gas superficial velocity (12 m/s), the average liquid holdups are 0.079, 0.070, and 0.067 for experiment with W71, S40, and S38. Here, the reduction of surface tension from 71 mN/m to 40 mN/m and 38 mN/m gives the reduction of liquid holdup to 92% and 82% from that of water.If the superficial gas velocity is increased to 25 m/s, with constant liquid superficial velocity, the liquid holdups decreaseto 0.0555, 0.0392, and 0.0316. The percentages of liquid holdup for experiment with S40 and S38 are then 71% and 57% from that of water. Further increase of gas superficial velocity to 40 m/s gives the liquid holdups of 62% and 56% for S40 and S38 from that of water. From these trends, it could be inferred that the higher gas superficial velocity gives the lower liquid holdup. This trend is valid for all the different surface tension used.

The effect of surface tension on the liquid holdup could also be seen in Figure 3. When the gas superficial velocity is low, the liquid holdup for experiment with W71, S40, and S38 are nearly the same (Figure 3a). It means that surface tension has a less significant effect on liquid holdup. If the gas velocity is increased (Figure 3b and c), itseffect is become clearer, indicated by the significant difference in liquid holdup.

The effect of liquid superficial velocity on the liquid holdup could be seen in Fig. 4. For gas superficial velocity of 40 m/s and liquid superficial velocity of 0.1 m/s, the average liquid holdups are 0.0420, 0.0312, and 0.0317 for experiment with W71, S40, and S38, respectively. The percentage of liquid holdup for S40 and S38, relative to W71, are 74% and 75%, respectively. Further increasing of liquid superficial velocity to 0.2 m/s gives the liquid holdups of 0.053, 0.0378, and 0.0377. Therefore, it could be concluded that increasing the liquid superficial velocity will also increase the liquid holdup.

At low gas superficial velocity, it is shown that the liquid holdup drops significantly when the liquid superficial velocity is high. On the other hand, when the gas superficial velocity is high, the greater reduction of liquid holdup occurs at low liquid superficial velocity.

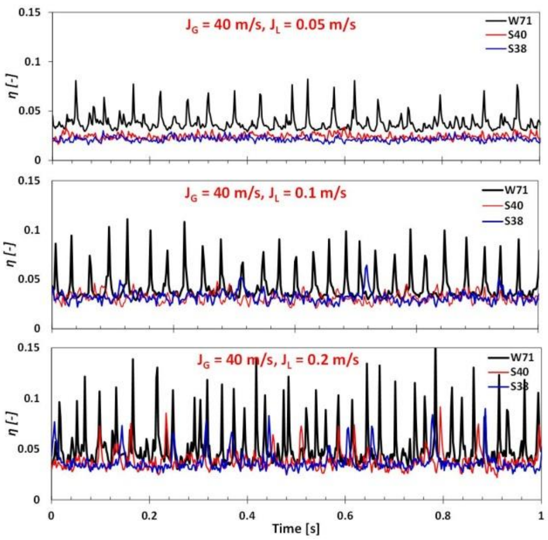

Figure 4. Effect of J_L and surface tension on the liquid holdup (J_L is varied from 0.05 to 0.2 m/s and J_G constant = 40 m/s).

The statistical analysis of liquid holdup using probability distribution function (PDF) is described in the following paragraph. The PDF of the liquid holdup signal for experiment with water are presented in Fig. 5 and 6. Narrower distribution is obtained for liquid holdup data under low liquid Reynolds number and high gas Reynolds number. On the other hand, wider holdup distribution is resulted by low gas Reynolds number and high liquid Reynolds number.

Detailed inspection of Figure 5 shows that under the lowest liquid Reynolds number (Re_L = 797), the peak of liquid holdup data for the lowest gas Reynolds number (Re_G = 13,952) is located at the interval of 0.04-0.05, in which 28.0% of all holdup data are located within this interval. Increasing the gas Reynolds number to Re_G = 20,928 does not shift the peak. However, more data are located in this interval (35.6%). For Re_G = 29,067, the peak is shifted to the interval of 0.03-0.04 and 76.4% data are located within the interval of 0.00-0.05. Further increaseof Re_G to 34,880gives the peak at the same interval. However, 88.9% data are located at the interval of 0.00-0.05. Finally, for the largest gas Reynolds number, Re_G = 46,506, the peak of PDF is located at the interval of 0.02-0.03. In addition, 95.8% data are located within the interval of 0.00-0.05 and all data (100%) are located within the interval of 0.00-0.10. Therefore, the higher gas Reynolds number shifts the PDF of liquid holdup to the smaller and narrower value.

For the liquid Reynolds number of 1594, the similar trend could be found. The distribution of liquid holdup is, however, not as sharp as that in the lower liquid Reynolds number. At Re_G = 13,952, the peak is located at the interval of 0.06-0.07, only 17.4% data are located within this interval, and only 1.6% data are located within the interval of 0.00-0.05. This shows that the distribution function is somewhat flat and the liquid holdup is quite large. Increasing Re_G to 29,067 under the same Re_L gives the peak at the interval of 0.03-0.04. 33.9% data are located within this peak interval and only 65.3% data are located within the interval of 0.00-0.05. Under the highest Re_G, the peak is located at the interval of 0.02-0.03, in which 63.0% data are located within it and 90.5% data are located within 0.00-0.05 interval.

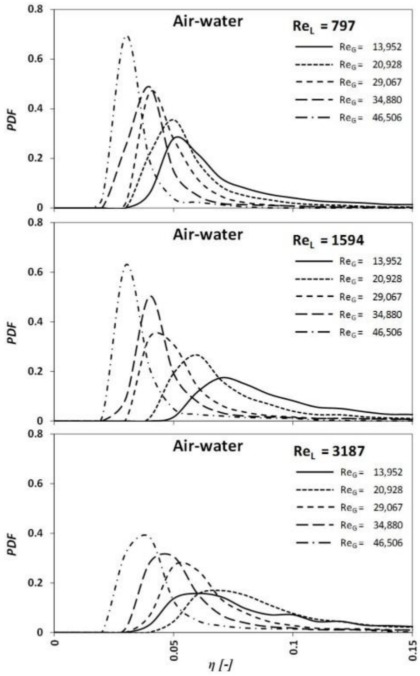

Figure 5.PDF of liquid holdup at constant Re_L and various Re_G for experiment withW71.

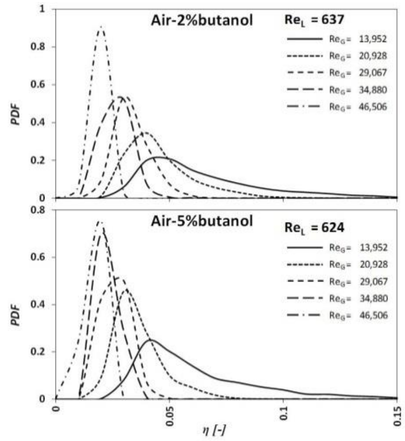

Figure 5.PDF of liquid holdup for experiment with 2% and 5% butanol solutions.

The similar trends for PDF are found for liquid of different surface tension. Figure 5 shows the PDF of liquid holdup for experiment with air and 2% butanol solution and air and 5% butanol solution with liquid Reynolds number of 637 and 624, respectively. It could be inferred from Figure 5 that 2% and 5% butanol solutions give the smaller liquid holdup, as could be seen by the location of the peaks of distribution functions compared to those of experiment with air and water.

To investigate the effect of liquid superficial velocity and surface tension on the liquid holdup, the probability distribution functions of 2% and 5% butanol solutions are presented in Figure 6. Under gas superficial velocity of 30 m/s and liquid superficial velocity of 0.05 m/s, the probability distribution function gives the peak at 0.04 for water, 0.03 for 2% butanol solution, and 0.03 for 5% butanol solution. The PDF at the peaks are 0.48, 0.52, and 0.70 for water, 2% butanol, and 5% butanol, respectively. Increasing the liquid superficial velocity to 0.1 m/s gives the peaks at 0.04, 0.03, and 0.03 with PDF of 0.50, 0.48, and 0.55 for water, 2% butanol, and 5% butanol, respectively. Under the highest liquid superficial velocity (0.2 m/s), the peaks are located at 0.05, 0.04, and 0.04 with the PDF of 0.31, 0.43, and 0.45 respectively. Qualitatively, the results are in accordance with [10,11,12,13].

The probability distribution function of liquid holdup in Figure 6 could also be analyzed qualitatively. The graphs demonstrate that the distributions are wider for experiment with higher liquid superficial velocity and higher surface tension. This indicates that the fluctuation of liquid holdup is higher for higher liquid superficial velocity and higher surface tension.

The liquid holdup fluctuation could also be analyzed using standard deviation of liquid holdup. Experiment with air and water gives the highest standard deviation of liquid holdup. Using air and 2% butanol, the standard deviation is lower. The lowest standard deviation is obtained for experiment with air and 5% butanol, where the surface tension is the lowest. Therefore, it could be inferred that the fluctuation of liquid holdup is low when the surface tension is low.

4. CONCLUSION

The experiment of gas-liquid horizontal annular flow has been carried out with different liquid surface tension. The liquid holdup decreases when the gas superficial velocity increases and the surface tension decreases. The PDF analysis shows that the fluctuation of liquid holdup distribution is high when the gas superficial velocity is low and liquid superficial velocity is high. From the standard deviation of liquid holdup, the fluctuation of liquid holdup is high when the surface tension is high.

ACKNOWLEDGEMENT

The authors wish to thank Mr. Ade IndraWijaya, Mr. AnamBahrul, and Mr. Guntur Purnama, the former student of the Department of Mechanical and Industrial Engineering, GadjahMada University, Indonesia, for their helpful support during the experiment in the Fluid Laboratory, Department of Mechanical and Industrial Engineering, GadjahMada University. Financial support from the Directorate General of Higher Education, the Ministry of Education and Culture of the Republic of Indonesia isalso gratefully acknowledged.

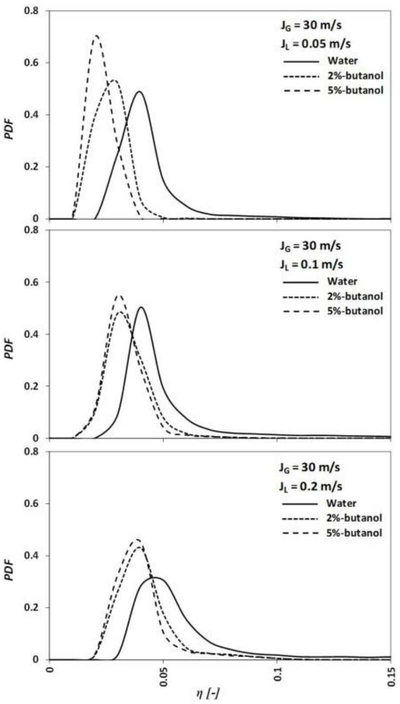

Figure 6.Effect of liquid superficial velocity on the PDF of liquid holdup for experiment with water, 2% butanol, and 5% butanol solutions.

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