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# Sub-Regimes of Air-Water Slug Flow Characteristics in Horizontal Pipes by Liquid Hold-up Model Correlated to Bubble Behaviors (LHmBb)

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ABSTRACT

The air-water slug flow sub regimes in horizontal pipes were characterized by a liquid hold-up model correlated to bubble behavior (LHmBb). The LHmBB has two sections, the liquid hold-up model and bubble behavior investigations. The liquid hold-up model was developed based on the statistical analysis of the probability density function (PDF) to quantify the bubble distribution. Specifically, the distribution was qualitatively investigated based on the high-speed camera and correlated to the quantified LH to characterize the sub-regime of air-water slug flow. The LHmBB characterized the air-water slug flow sub-regimes in a horizontal transparent acrylic pipe with an inner diameter of Ø= 0.026 m under air and water superficial velocities of $J_G = 0.31 - 6.00$ m/s $J_L = 0.20 - 0.44$ m/s, respectively. As a result, four sub-regimes were determined as Initially dispersed Bubbles (IdB), Low dispersed Bubbles (LdB), High dispersed Bubbles (HdB), and Dominantly dispersed Bubbles (DdB). The decreasing number of bubbles and dispersing bubbles mechanism determined the type of sub-regime. The proposed LHmBb included the correlation function to ease the prediction of the sub-regimes of air-water slug flow characteristics, leading to the two-phase flow pattern map in horizontal pipes enhancement.

## 2.1. INTRODUCTION

In industrial applications, air-water two-phase flow inside the pipes occurs in various ways. For instance, during the transition stages, growing waves in the oil and gas refinery piping system generate high oscillatory pressure. This leads to high vibrations on the piping structure, causing cracking and corrosion [1]. The

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transition stages covering the initiation through the intermittent to the developed flow were characterized by the air-water two-phase flow inside the pipes, valuable for minimizing the damage in the pipes. Previous studies focused on understanding the complex characteristics of the developed flow, including limited works on the initiation and the intermittent flow. In our previous studies, the initiation and development flow were experimentally investigated in a horizontal pipe resulting in several basic characteristics of slug flow initiation evaluated by slug initiation and the passing slug frequency [2]. Arabi et al. investigated the slug flow characteristic in the intermittent flow by its frequency with an empirical correlation to the experimental data based on the liquid volume fraction, to respond to the initiation flow characteristics [3]. Therefore, a deep understanding of the sub-regime of air-water slug flow characteristics inside the pipes helps prevent the drawbacks in the industrial pipelines.

The characteristics of air-water slug flow sub regimes were proposed by several related studies. The characteristics include Kelvin-Helmholtz (KH) instability of a stratified flow, viscous linear instability of a stratified flow by long is long-wavelength (VLW), and stability of a slug flow [4]. The KH instability explained that the mechanism of wave growth for inviscid fluid is not feasible for predicting the actual sub-regimes of air-water slug flow characteristics because the fluid has no viscosity [5]. The VLW instability is also known as Viscous Kelvin-Helmholtz (VKH), which provides a better prediction. The VLW instability is analyzed based on the growth of small amplitude, long wavelength disturbances and shear stresses, and destabilizing effects of liquid inertia. However, the VLW instability is difficult to be observed for sub-regime of air-water slug flow characteristics [6]. The VLW instability was upgraded by Hurlburt and Hanratty [7] in terms of stability compared to the slug stability theory proposed by Taitel and Dukler [5]. This was achieved by determining the relationship between the bubble velocity and the mixture velocity to estimate the critical height of the liquid layer. Based on the above studies, the details investigation of bubble parameters is important for characterizing the sub-regimes of air-water slug flow.

In order to investigate the details of bubble parameters, several previous works by means of liquid hold-up model were reported. Conventionally, an electrical impedance was used to measure the experimental liquid hold-up with respect to the threshold value to determine the flow regime [8]. On the other hand, a constant-electrical-current method (CECM) was used to determine the time varying thickness of liquid film flowing with high-speed gas flow [9]. Up to now, vast improvement on liquid hold-up model is introduced to provide more comprehensive analysis compared to the conventional one. In our previous research, the air-water slug flow sub regimes were characterized in 16 mm horizontal pipe based on the experimental liquid hold-up and pressure fluctuations [10]. The simplified correlation was proposed for vast prediction of experimental liquid hold-up in annular flow as comprehensive analysis [11]. Since the liquid hold-up covers the complex characteristics in a wide range of flow regimes, a correlation model to bubble behavior is considered.

In order to comprehensively characterize the air-water slug flow sub regimes in horizontal pipes, a liquid hold-up model correlated to bubble behaviors (LHmBb) was proposed. This study aimed to 1) quantify the bubble behaviors in sub-regimes of air-water slug flow, 2) determine the characteristics of sub-regimes air-water slug flow by LHmBb, and 3) develop a correlation function based on LHmBb for the prediction model of the characteristics of sub-regimes air-water slug flow. This work is dedicated to support the theoretical model development and validation of CFD codes [12], [13] by high-quality temporal and spatial experimental data of air-water slug flow sub-regimes. Moreover, the proposed model is valuable for the development of advanced machine learning for two-phase flow application, such as a comprehensive input model in plural long short-time memory with sparse model implemented in multiple current-voltage system (pLSTM-SM-MCV) [14].

## 2.2. LIQUID HOLD-UP MODEL CORRELATED TO BUBBLE BEHAVIOURS(LHmBb)

### 2.1 Overview

The liquid hold-up model was developed based on the statistical analysis of probability density function (PDF) to quantify the bubble distribution. The bubble behaviors are qualitatively investigated based on the high-speed camera and correlated to the quantified LH to characterize the air-water slug flow sub-regimes.

### 2.2 Liquid hold-up model

The fundamental equation of the constant-electric-current-method (CECM) proposed by [9] defined the liquid hold-up model (LHm) where the electric resistance of two-phase flow R_TP in a unit length of the horizontal pipe is expressed as,

$$\frac{1}{R_{TP}} = \frac{1-\alpha}{R_G} + \frac{\alpha}{R_L} \tag{1}$$

Where $R_G$ is the gas resistance, $R_L$ liquid resistance, and $\alpha$ liquid hold-up. Both $R_G$ and $R_L$ represent the electric resistance when the gas and liquid phases occupy the horizontal pipe's whole cross-section. In the case of $R_G \gg R_L$, Eq. (1) can be defined as relating to the voltage drop $V_{TP}$ and injected constant current $I$ as,

$$\alpha = \frac{IR_L}{IR_{TP}} = \frac{V_L}{V_{TP}} \tag{2}$$

Since the voltage drop $V_L$ refers to the case of liquids occupies the whole horizontal pipe's cross-section while flowing, the electric resistance $R_{TP}^{ref}$ and voltage drop $V_{TP}^{ref}$ of two-phase flow with the reference liquid hold-up $\alpha^{ref}$ can be defined by firstly modifying Eq. (2) with respect to I and secondly eliminating $V_L$ as,

$$\alpha^{ref} = \frac{IR_L}{IR_{TP}^{ref}} = \frac{V_L}{V_{TP}^{ref}} \tag{3}$$

$$\alpha = \frac{IR_{TP}^{ref}}{IR_{TP}} \alpha^{ref} = \frac{V_{TP}^{ref}}{V_{TP}} \alpha^{ref} \tag{4}$$

Therefore, the $\alpha$ of the air-water two-phase flow in the horizontal pipe in Eq. (4) can be determined.

### 2.3 Quantified bubble behaviors

The bubble behaviors $\beta$ are quantified based on the normalized number of bubbles $\beta_H$, that occupies the whole section of the horizontal pipe during the air-water slug flow. Here, $\kappa$ is the air-water slug flow patterns which corresponds to the superficial velocity of gas $J_G$ and liquid $J_L$, respectively. The $\beta_H$ is normalized by the number of bubbles $\beta^{ref}$, corresponding to their momentum in air-water two-phase flow. $\beta^{ref}$ is the maximum value of the air-water two-phase flow's voltage drop $V_{TP}$ in Eq. (4) under specific $\kappa$. According to the normalization the technique used by [15], which quantifies the two-phase sludge thickness in centrifugal fields, $\beta$ can be defined as,

$$\beta = \frac{\beta_\kappa - \beta_\kappa^{ref}}{\beta_\kappa^{ref}} \tag{5}$$

To solve Eq. (6), image processing techniques (IPT) which has been applied in our previous works [16], [17] is referred to quantify the bubble behaviors captured by high-speed camera. The IPT assessed the area of bubble data, equivalent diameter, and perimeter in case of a break-up, traveled, detached/coincided, and dispersed bubble. An active morphological contour without edges (MACwE) technique was used for processing images with visible contours inthe condition of noisy, cluttered, or partially unclear images. The three main steps of MACwE are; 1) thresholding and shading, 2) segmentation and 3) binarization and evolutions. The $\beta_H$ was obtained from the three iterations category denoted as $a$, $b$, and $c$, which represented the area of the bubbles under $\kappa$. Where $\beta$ is from the known $\beta^{ref}$of the whole binary numbers under $\kappa$.

$$\alpha' = \frac{V_{TP}^{ref}}{\beta V_{TP}} \alpha^{ref} \tag{6}$$

Thus, the quantitative LHmBb From Eq. (6) is evaluated by the probability density function (PDF), denoted as $P$ as follows,

$$P(\alpha^0 \leq \alpha' \leq \alpha^m) = \int_{\alpha^0}^{\alpha^m} f_{\alpha'}(\alpha) d\alpha \tag{7}$$

Where $\alpha^0$ and $\alpha^m$ are the lowest and highest liquid hold-up, respectively, can be measured in the whole section of liquid hold-up.

### 2.4 Correlation model

In order to correlate the LHm for sub-regime of air-water slug flow characteristics, the quantified bubble behaviors $\beta$ in Eq. (5), with respect to LHm in Eq. (4), is defined as,

$$\alpha' = \frac{V_{TP}^{ref}}{\beta V_{TP}} \alpha^{ref} \tag{6}$$

## III EXPERIMENTS

### 3.1. Experimental setup

The experiments were carried out at Horizontal Two-Phase Flow Facility (HORTOFF)-Fluid Mechanics Laboratory, Department of Mechanical and Industrial Engineering, Faculty of Engineering, Gadjah Mada University, Indonesia. **Figure 1** shows the experimental setup consisting of an inlet, test, and outlet sections. The inlet section configured the air-water mixer installed to keep the air and the water flow separately into the test section. The air and water were from the top and bottom sections of the mixer, respectively. For the initial flow alignment and modification of the two-phase flow into a stratified one, a splitter plate was installed at the center of the air-watermixer, as used by Ujang et al. [19] from the former experiments [2], [13], [16], [18]. The test section was composed of a horizontal pipe with a 9 m length and an inner pipe diameter of 0.026 m. The length of the test section is designed for 0-210 of diameter (0-210D) or around 5.46 m to guarantee a stable development of air-water slug flow. The use of the same materials on the entire experimental pipe ensured uniform roughness of the wall. In the outlet section, the ends of the horizontal pipe and each flange were machined to give and maintain smooth junctions and pipes and minimize the gaps.

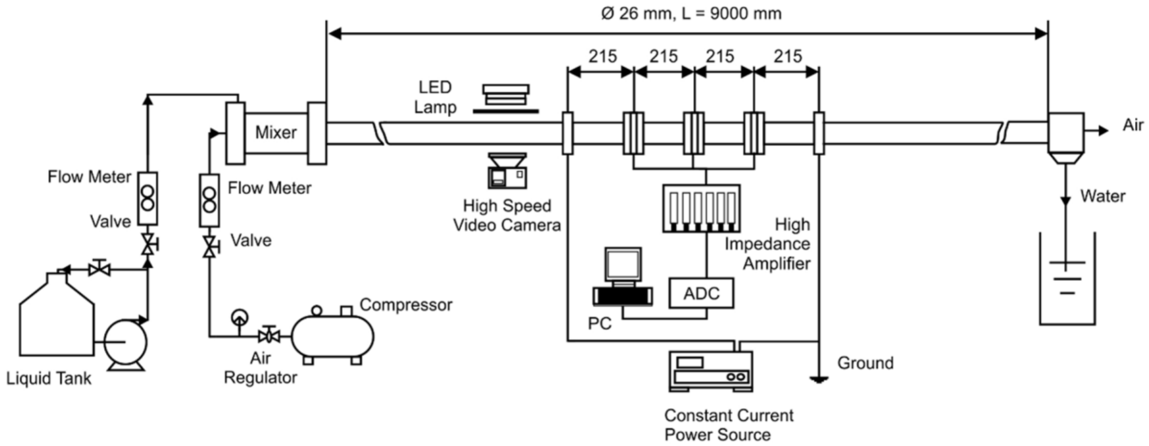


**Figure 1.** Schematic diagram of the experimental setup.

A room temperature and an atmospheric pressure were maintained during the experiment. On the inlet section, air pressure of 8 bars (gauge) was supplied by a compressor and a maximum amountof 600 LPM. A centrifugal pump with minimum fluctuations compared to other pumps, with a capacity of 18 $m^3/h$, pumped the water into the section. The installation of a flexible hose on the inlet section rig reduces the flow oscillations and vibrations. To control the flow rate, two types of flow meters were used, namely 1) Dwyer's gas flow meters with capacities range of 1-600 SCFH and 300-1,800 SCFH, and a 3% accuracy and 2) Omega water flow meters with maximum capacity of 10 GPM and an approximate 2% accuracy.

A constant-electric-current method (CECM) with three parallel sensors located at a 215 mm distance was used to obtain the liquid hold up defined in Eq. (6). Bubble behaviors were observed within 120 seconds, focusing on a specific point before the developed flow's measurement points. A high-speed video camera, Phantom Miro-M310, with a maximum frame rate of 1,200 fps and a resolution of 3,000 x 4,000 pixels, was installed at 150D, obtaining the spatial results of visualization studies. The lighting equipment had a series of installed LED lamps on the test section rig. Regarding the distortion from the horizontal pipe, a correction box was installed in the test section pipe, about 5 m from the inlet section. The box reduced image distortion and minimized the difference in refractive indices between the fluids and tube wall [20]. It was made of a rectangular transparentacrylic box filled with water with a refractive index. Therefore, the quality of visualization data could be highly-maintained. The phenomenon in the near-wall was magnified for a better investigation of sub-regime of air-water slug flow characteristics.

### 3.2. Experimental method and condition

The experimental matrix had a range of air and water superficial velocities as $J_G = 0.31 - 6.00$ m/s and $J_L = 0.20 - 0.44$ m/s. The low-liquid superficial velocities observations were conducted to investigate the transition phenomenon in the presence of the bubbles. At the higher liquid superficial velocities, the focus was on the presence of bubble under the wave coalescence, the pipe blockage due to wave growth, turbulence penetration, and its relationto the sub-regime phenomenon. Under the high liquid, superficial velocities were to investigate the presence of bubbles pressured by the irregular waves and the initiation positionsof the slug flow. The experimental data were obtained in two stages carried out simultaneously. a) the visualization observation for quantifying the bubble behaviors and b) liquid hold-up measurements.

## IV RESULTS AND DISCUSSIONS

### 4.1 Bubble behaviors in sub-regime air-water slug flow

**Figure 2** shows the qualitative visualization of the bubbly tail of sub-regime air-water slug flow for quantifying their behaviors. Bubble behaviors in the bubbly tail, based on the qualitative visualization, defined the sub-regime flow patterns as Initially dispersed Bubbles (IdB), Low dispersed Bubbles (LdB), High dispersed Bubbles (HdB), and Dominantly dispersed Bubbles (DdB). At the bubble tail of IdB, an elongated narrow, shaped bubble that flowed along the upper side of the pipe occurred due to the higher momentum of the liquid, which increased the speed of the flowing bubble, streamlining the bubble nose. High friction along the pipe surface, near thewall, the air-water two-phase flow sheered away from the edge of the pipe. This triggers a transition from the plug into a slug, leading to the bubbles' initial break-up, as shown in **Fig. 2 (a)**. The bubble tail exerted by the high momentum of liquid caused the dispersal of the small bubbles in the liquid slug. Moreover, several bubbles traveled occurred in the slug- bubbly tail.

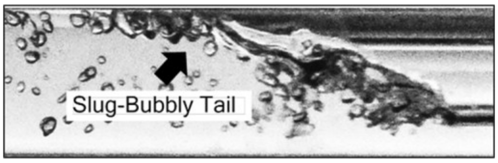


**Figure 2a.** Bubble behaviors characteristics in sub-regime of air-water slug flow. Initially dispersed Bubbles (IbB) $J_G = 0.70$ m/s and $J_L = 0.44$ m/s

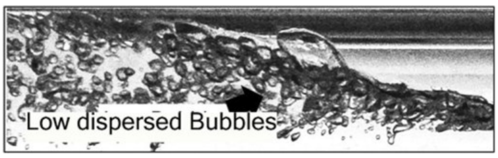


**Figure 2b.** Bubble behaviors characteristics in sub-regime of air-water slug flow. Low dispersed Bubbles (LdB) $J_G = 1.26$ m/s and $J_L = 0.31$ m/s

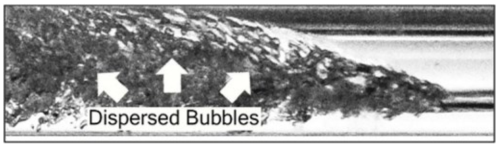


**Figure 2c.** Bubble behaviors characteristics in sub-regime of air-water slug flow. High dispersed Bubbles (HdB) $J_G = 1.88$ m/s and $J_L = 0.44$ m/s

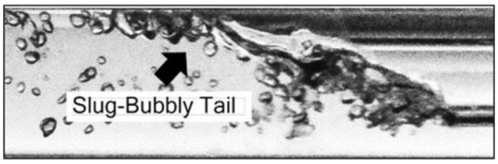


**Figure 2d.** Bubble behaviors characteristics in sub-regime of air-water slug flow. Dominantly dispersed Bubbles (DdB) $J_G = 6.00$ m/s and $J_L = 0.31$ m/s

In the higher momentum of gas, the LdB is a low slug flow of bubbles in the slug-bubbly tail. The LdB flow occurred, as shown in **Fig. 2 (b)**, due to the momentumof the elongated bubble that drives the slug liquid phase to flow at a faster velocity. The elongated bubble momentum affects the development of the slug [21]. The superficial velocity of the gas is higher than the IdB; hence, the slug-bubbly tail is moreaerated. The higher momentum of both gas and liquid shows the linear tendency. As shown in **Fig. 2 (c)**, the HdB is the numerous dispersed bubbles in the slug-bubbly tail. They are also known as aeration. They occur continuously and intensively at the air-water interface, inside the slug-bubbly tail [22], where the liquid slug is more aerated and becomes chaotic than within LdB. The higher momentum of the gas.

Affects the entrainment in the liquid slug front traveled to the slug-bubbly tail. The traveled bubbles in HdB penetrated the interface of the slug tail and disrupted the elongated thin layer of bubbles. The DdB is defined as the HdB with a wavy interface. **Fig.2 (d)** shows how the wavier interface at the liquid slug front and slug-bubbly tail are more chaotic than HdB. The smaller dispersed bubbles disrupted the elongated bubbles and caused the wavy interfaces. The dynamic changes of gas and liquid momentum led to different characteristics of sub-regimes of air-water slug flow based on the four proposed flows. The massive dispersed bubbles in the highest momentum caused structural damage to the elbow, knee, tee, nozzle, and diffuser.

**Figure 3** shows the quantified bubble behaviors obtained from Eq. (5) in sub-regimes of air-water slug flow. The quantification of the four characteristics of sub-regime air-water slug flow in the horizontal pipe was based on the bubble behaviors obtained by qualitative visualization. Gas and high liquid momentum forced the bubbles to be distributed in the wider area inside the slug-bubbly tail.

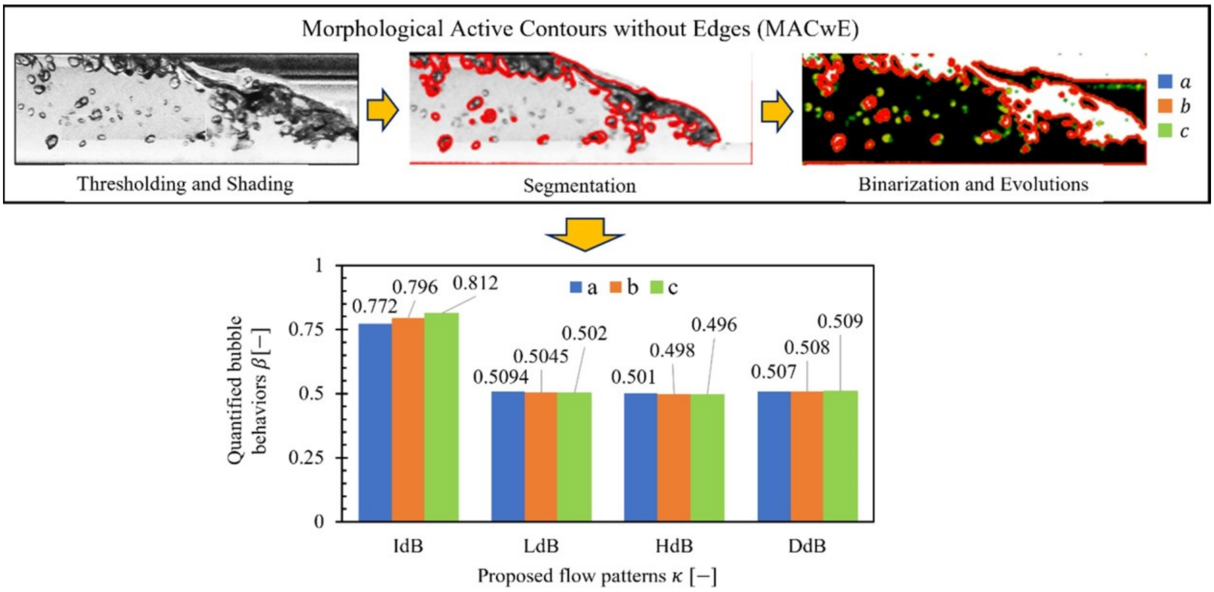


**Figure 3.** Quantified bubble behaviors $\beta$ in the sub-regime of air-water slug flow.

### 4.1 Characteristics of sub-regime air-water slug flow by LHmBb

**Figure 4** shows the liquid hold-up obtained from Eq. (6) in sub-regimes of air-water slug flow. The characteristics of sub-regime air-water slug flow are divided into three stages which are 1) the occurrence of liquid plug reflected by the probability density function $P$ at the liquid hold-up $\alpha = 0.8$ —[—], 2) the occurrence of plug bubbles represented the dispersed bubble behaviors reflected by $P$ at $\alpha = 0.4$ — 0.8 [—], and 3) the high momentum of slug bubbles symbolized the higher momentum of dispersed bubble behaviors reflected by $P$ at $\alpha = 0.1$ — 0.3 [—]. The initially dispersed bubble (IdB) flow has a higher momentum than slug bubbles, as shown in **Fig. 4 (a)**. Four different segmentations in heights denoted as $y$ were proposed with a distance of $0.25D$ to illustrate characterization as seen from the distribution of brightness level $B$ to the observed length $x$, the bubbles dispersed were observed by the low fluctuation of $B$ alongside $x$. The linear tendency of the increasing number of dispersed bubbles and the momentum was correlated to the increasing $P$ at lower $\alpha$. From the mass conservations view, the smaller size of dispersed bubbles distributes uniformly, leading to lower momentum compared with the liquid plug under IdB. These are validated by the changes of distribution of $P$ from $\alpha = 0.8$ — 1.0 [—] under LdB and HdB to $\alpha = 0.1$ — 0.3 [—] under DdB. Moreover, the frequency of $B$ alongside $x$ is dense, agreeing with the tendency of static pressure and slug frequency proposed by [2]and [3]. The approach based on image processing was infeasible for industrial applications. The *in situ* measurements based on LH correlated to the bubble behaviors are good for the rapid decision making on the real scale ofair-water two-phase flow.

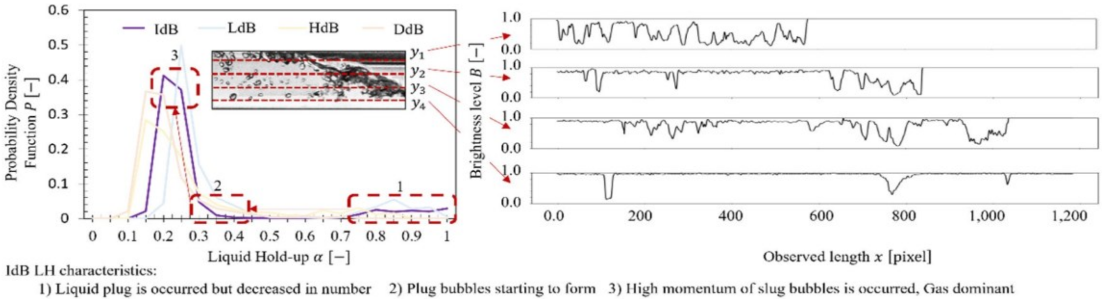


**Figure 4a.** Liquid hold-up $\alpha$ characteristics in sub-regime of air-water slug flow. Initially dispersed Bubbles (IbB) $J_G = 0.70$ m/s and $J_L = 0.44$ m/s

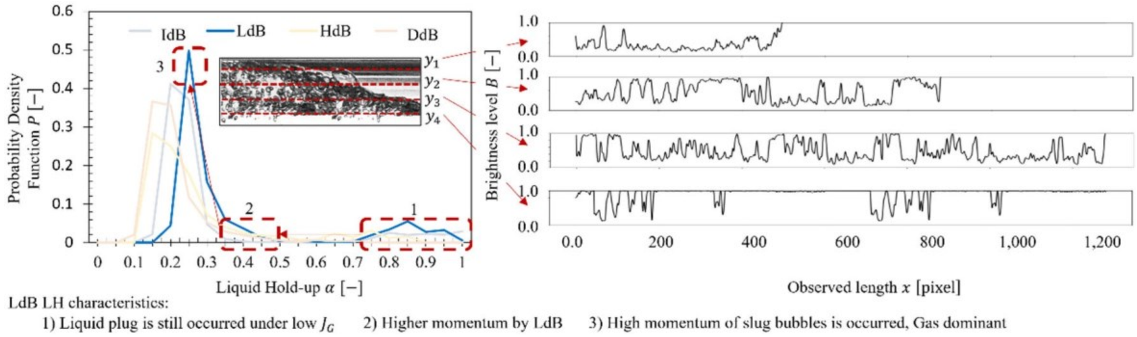


**Figure 4b.** Liquid hold-up $\alpha$ characteristics in sub-regime of air-water slug flow. Low dispersed Bubbles (LdB) $J$G = 1.26 m/s and $J$L = 0.31 m/s

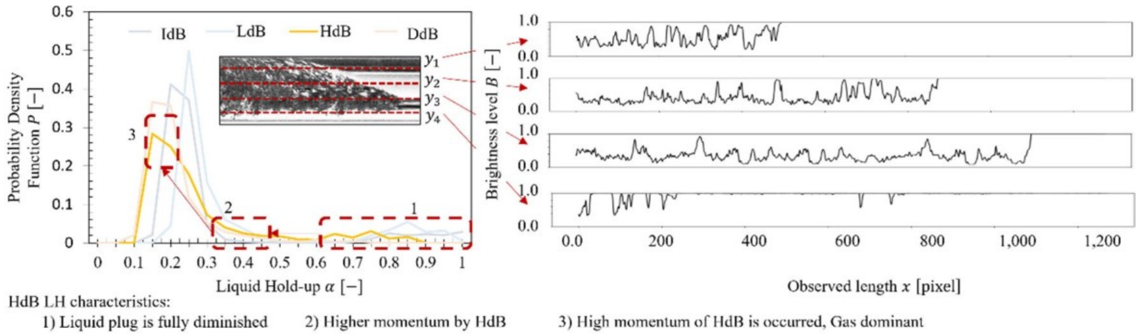


**Figure 4c.** Liquid hold-up $\alpha$ characteristics in sub-regime of air-water slug flow High dispersed Bubbles (HdB) $J$G = 1.88 m/s and $J$L = 0.44 m/s

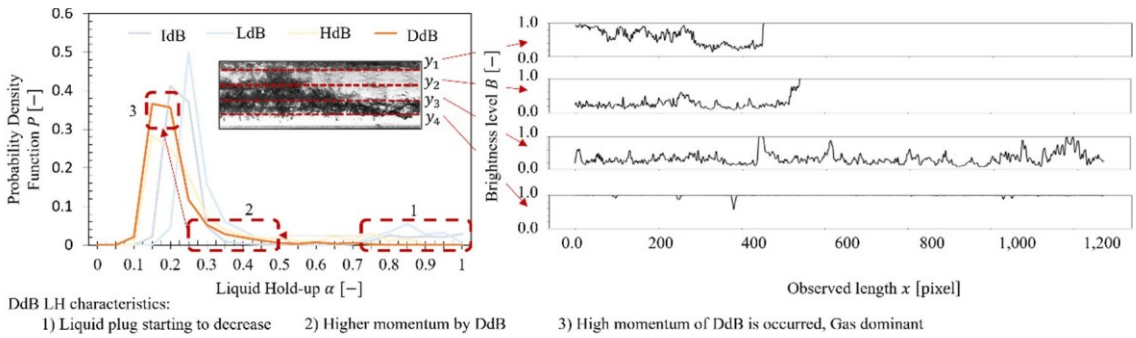


Figure 4d. Liquid hold-up $\alpha$ characteristics in sub-regime of air-water slug flow. Dominantly dispersed Bubbles (DdB) $J$G = 6.00 m/s and $J$L = 0.31 m/s

### 4.2 Correlation function of LHmBb for predicting sub-regime air-water slug flow

**Figure 5** shows the correlation function of LHmBb for predicting sub-regime air-water slug flow in horizontal pipe based on three dominant liquid hold-ups $\alpha$ defined in **section 4.2**. Each $\alpha$ is defined as the average value within the three stages. The most dominant value of probability density function $P$ is plotted in three $\alpha$ based on the three points for the simplified polynomial correlation function as,

$$P' = \varsigma_1\alpha^2 - \varsigma_2\alpha + \varsigma_3 \qquad (8)$$

**Equation (7)** is solved in **Table 1**. As shown in **Fig. 5**, the three stages were used to predict sub-regime air-water slug flow characteristics with the pivot $\alpha$, which determines the changes in flowpatterns. Moreover, the correlation function of LHmBB $P'$ has a low error based on the comparison between $P$ and $P$. 'To provide comprehensive validations, the proposed $P'$ was planned to be verified by previous models and tested as the input of a machine learning application for predicting the $\alpha$, flow regimes, and bubble velocities.

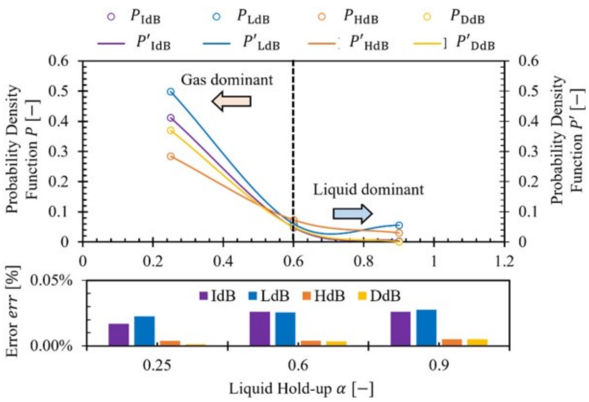


**Figure 5.** Liquid hold-up characteristics in sub-regime of air-water slug flow.

**Table 1** Coefficients and error rate of the proposed correlation function $P'$.

| $\kappa$ | $\varsigma_1$[—] | $\varsigma_2$[—] | $\varsigma_3$[—] | $\langle err \rangle$[%] |
|---|---|---|---|---|
| IdB | 1.366 | 2.200 | 0.876 | 0.023 |
| LdB | 1.899 | 2.866 | 1.096 | 0.025 |
| HdB | 0.707 | 1.204 | 0.541 | 0.004 |
| DdB | 1.150 | 1.892 | 0.771 | 0.003 |

## V CONCLUSION

In this study, the characteristics of the sub-regimes of air-water slug flow in the horizontal pipe by the proposed liquid hold-up model correlated to bubble behaviors (LHmBb) can be summarized as follows.

The quantified bubble behaviors in terms of $\beta$ were obtained by the image processing technique based on the active morphological contour without edge (MACwE) technique processed in Python 3.8. The $\beta$ is decreasing under different flow regimes and gives a minor explanation of the bubble distribution in the sub-regimes air-water slug flow. The difference of $\beta$ is caused by the less sensitivity of $\beta_H$ obtained from MACwE. An improved algorithm provided a more detailed segmentation, and binarization was planned for the future works,

The LHmBb successfully determined the sub-regimes air-water slug flow characteristics with qualitative analysis and provide the understanding of the previous works. The four characteristics, defined as Initially dispersed Bubbles (IdB), Low dispersed Bubbles (LdB), High dispersed Bubbles (HdB), and Dominantly dispersed Bubbles (DdB), provided a new finding regarding the sub-regimes air-water slug flow in a horizontal pipe.

The correlation function offered a high accuracy prediction of the air-water slug flow regimes sub-regimes. A comprehensive correlation was required to elaborate on the important slug flow mechanism and contribute to the development of air-water two-phase flow in a multiphase flow society.

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## References

[1] J. Villarreal, D. Laverde, and C. Fuentes, "Carbon-steel corrosion in multiphase slug flow and CO2," *Corros. Sci.*, vol. 48, no. 9, pp. 2363–2379, 2006,

doi: 10.1016/j.corsci.2005.09.003.

[2] O. Dinaryanto *et al.*, "Experimental investigation on the initiation and flow development of gas-liquid slug two-phase flow in a horizontal pipe," *Exp. Therm. Fluid Sci.*, vol. 81, pp. 93–108, Feb. 2017.

[3] A. Arabi, Y. Salhi, Y. Zenati, E. K. Si-Ahmed, and J. Legrand, "On gas-liquid intermittent flow in a horizontal pipe: Influence of sub-regime on slug frequency," *Chem. Eng. Sci.*, vol. 211, p. 115251, 2020, doi: 10.1016/j.ces.2019.115251.

[4] M. Fernandino and T. Ytrehus, "Determination of flow sub-regimes in stratified air-water channel flow using LDV spectra," *Int. J. Multiph. Flow*, vol. 32, no. 4, pp. 436–446, 2006, doi: 10.1016/j.ijmultiphaseflow.2006.01.003.

[5] Y. Taitel and A. E. Dukler, "A model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow," *AIChE J.*, vol. 22, no. 1, pp. 47–55, 1976, doi:10.1002/aic.690220105.

[6] P. Y. Lin and T. J. Hanratty, "Prediction of the initiation of slugs with linear stability theory,"

*Int. J. Multiph. Flow*, vol. 12, no. 1, pp. 79–98, 1986, doi: 10.1016/0301-9322(86)90005-4.

[7] E. T. Hurlburt and T. J. Hanratty, "Prediction of the transition from stratified to slug and plug flow for long pipes," *Int. J. Multiph. Flow*, vol. 28, no. 5, pp. 707–729, 2002, doi: 10.1016/S0301-9322(02)00009-5.

[8] P. Andreussi, A. Di Donfrancesco, and M. Messia, "An impedance method for the measurementof liquid hold-up in two-phase flow," *Int. J. Multiph. Flow*, vol. 14, no. 6, pp. 777–785, 1988, doi: 10.1016/0301-9322(88)90074-2.

[9] T. Fukano, "Measurement of time varying thickness of liquid film flowing with high-speed gas flow by a constant electric current method (CECM)," *Nucl. Eng. Des.*, vol. 184, no. 2–3, pp. 363–377, 1998, doi: 10.1016/S0029-5493(98)00209-X.

[10] O. Dinaryanto, A. Widyatama, M. Prestinawati, Indarto, and Deendarlianto, "The characteristics of the sub regime of slug flow in 16 mm horizontal pipe," *AIP Conf. Proc.*, vol. 2001, 2018, doi: 10.1063/1.5049980.

[11] A. Setyawan, Indarto, and Deendarlianto, "Simplified correlation for liquid hold-up in a horizontal two-phase gas-liquid annular flow," *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 62, no.1, pp. 20–30, 2019.

[12] Deendarlianto, T. Höhne, P. Apanasevich, D. Lucas, C. Vallée, and M. Beyer, "Application of a new drag coefficient model at CFD-simulations on free surface flows relevant for the nuclear reactor safety analysis," *Ann. Nucl. Energy*, vol. 39, no. 1, pp. 70–82, 2012, doi: 10.1016/j.anucene.2011.09.010.

[13] A. W. O. D. K. I. Deendarlianto Moeso Andrianto, "CFD Studies on the gas-liquid plug two- phase flow in a horizontal pipe," *J. Pet. Sci. Eng.*, vol. 147, pp. 779–787, Sep. 2016, doi: 10.1016/j.petrol.2016.09.019.

[14] K. Tanaka, Y. A. K. Prayitno, P. A. Sejati, D. Kawashima, and M. Takei, "Void Fraction Estimation in Vertical Gas-Liquid Flow by Plural Long Short-term Memory with Sparse Model Implemented in Multiple Current-Voltage System (pLSTM-SM-MCV)," *Multiph. Sci. Technol.*, 2021, doi: 10.1615/multscientechn.2021039801.

[15] Y. A. K. Prayitno, T. Zhao, Y. Iso, and M. Takei, "In situ measurement of sludge thickness in high-centrifugal force by optimized particle resistance normalization for wireless electrical resistance detector (WERD)," *Meas. Sci. Technol.*, vol. 32, no. 3, p. 034001, Mar. 2021, doi:10.1088/1361-6501/abc108.

[16] A. Widyatama, O. Dinaryanto, Indarto, and Deendarlianto, "The development of image processing technique to study the interfacial behavior of air-water slug two-phase flow in horizontal pipes," *Flow Meas. Instrum.*, vol. 59, no. October 2017, pp. 168–180, 2018, doi: 10.1016/j.flowmeasinst.2017.12.015.

[17] W. E. Juwana, A. Widyatama, O. Dinaryanto, W. Budhijanto, Indarto, and Deendarlianto, "Hydrodynamic characteristics of the microbubble dissolution in liquid using orifice type microbubble generator," *Chem. Eng. Res. Des.*, vol. 141, pp. 436–448, 2019, doi: 10.1016/j.cherd.2018.11.017.

[18] Deendarlianto, A. Z. Hudaya, Indarto, and K. D. Ozzilenda Soegiharto, "Wetted wall fraction of gas-liquid stratified co-current two-phase flow in a horizontal pipe with low liquid loading," *J. Nat. Gas Sci. Eng.*, vol. 70, no. May, p. 102967, 2019, doi: 10.1016/j.jngse.2019.102967.

[19] P. M. Ujang, C. J. Lawrence, C. P. Hale, and G. F. Hewitt, "Slug initiation and evolution in two-phase horizontal flow," *Int. J. Multiph. Flow*, vol. 32, no. 5, pp. 527–552, 2006, doi: 10.1016/j.ijmultiphaseflow.2005.11.005.

[20] A. Kawahara, P. Y. Chung, and M. Kawaji, "Investigation of two-phase flow pattern, void fraction and pressure drop in a microchannel,"

*Int. J. Multiph. Flow*, vol. 28, no. 9, pp. 1411–1435, 2002, doi: 10.1016/S0301-9322(02)00037-X.

[21] J. Thaker and J. Banerjee, “Characterization of two-phase slug flow sub-regimes using flow visualization,” *J. Pet. Sci. Eng.*, vol. 135, pp. 561–576, 2015, doi: 10.1016/j.petrol.2015.10.018.

[22] A. Arabi, Y. Salhi, A. Bouderbal, Y. Zenati, E. K. Si-Ahmed, and J. Legrand, “Onset of intermittent flow: Visualization of flow structures,” *Oil Gas Sci. Technol.*, vol. 76, no. April, 2021, doi: 10.2516/ogst/2021009.