The Study of Plug Flow Characteristics of Gas-Liquid Two-Phase Flow in A Horizontal Pipe by Using An Image Processing Technique

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Abstract: An image processing technique is an advantageous technique for many applications. For two-phase flow, this technique is used to investigate the flow characteristics such as interfacial behavior, flow topology, and bubble tracking. This paper presents a study of the characteristics of plug flow in a horizontal pipe by using an image processing technique. Sequences of images in videos were automatically analyzed in order to analyze plug flow topology included the characteristics of elongated bubble (visualization results, velocity, and liquid film thickness). In the present works, the video data from experiment were extracted into sequences of images by Virtual Dub software and for the data processing used MATLAB software. The image processing technique including image conversion (RGB to Grayscale image), background subtraction, noise reduction (image filtering), image adjustment, image thresholding, and binarization resulted binary images that could be automatically analyzed by digital (1 and 0) logic, depended on the threshold value. The study revealed that the measured variables such as the elongated bubble velocity and liquid film thickness could be accurately determined by the present technique. The difference of bubble nose coordinate was used to determine the elongated bubble velocity. Real size of measurement were acknowledged by calibration procedure (pixel to millimeter). As a result, it was found that the important flow parameters was observed has a good agreement between the physical experiment.

Keywords: Plug flow, image processing technique, flow topology, elongated bubble, binary image

1. Introduction

Gas-liquid two-phase flows are encountered in several engineering applications involving the phase change such as boiling process (power generation), heat exchanger, geothermal power plant, nuclear reactor, and petroleum industry. Slug flow has received special attention due to the flow stability and pressure fluctuation. In the horizontal pipe, slip between two-phase, and friction (between liquid slug and inner surface of pipe) lead the extreme pressure fluctuation. The larger fluctuation of local pressure difference ($\Delta P/\Delta L$) causes worst case of pipe blasting. To initiate the presence of slug flow, the study of plug flow characteristics become important.

Many experimental techniques have been used to particularize gas-liquid two-phase flow characteristics. Some examples are capacitance sensor **[1]**, wire mesh sensor **[2]**, signal processing by Constant Electric Current Method (CECM) **[3]**, X-ray tomography **[4]**, ultrasonic devices **[5]**, advanced optical instrumentation **[6]**, and high-speed video camera **[7]**.

The identification of slug flow characteristics by visualization technique is still developing by various methods. Gopal and Jepson **[8]** conducted velocity profile, transverse velocity, void fraction distribution, liquid hold-up in slug flow, and bubble diameters by manual edge tracking technique of the images for slug flow in horizontal pipe. Digital image analysis were used to study flow

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visualization of dynamic slug flow characteristics **[9]**. Van Hout et al. **[10]** conducted that elongated bubble velocity was determined by the difference of bubble nose coordinate and the number of frame needed (related to time difference in fps - frame per second). Beside of them, CFD modelling were also proposed by some researchers to get better explanation of flow characteristics **[11, 12, 13]**.

The complexity in two-phase flow phenomena often embroils related to flow characteristics and interfacial problem. Several cases of flow visualization results could not describe well about interfacial behavior, flow topology, and bubble tracking. Moreover, there several methods had been proposed by previous researchers in purpose to solve those problems. Although the results can be obtained by CFD modelling, several cases still need a better understanding of important flow parameter. A simpler but accurate technique is needed to validate the CFD codes

Sometimes, those methods only could be applied in certain circumstances, but also found contradictory. On the other hand, the researchers need to solve large quantities of visualization data which contain different information contents. Hence, the use of digital device that capable to process them is needed. Image processing technique is a powerful technique to investigate two-phase flow phenomena. This method provides better understanding of important flow parameter that common difficult to be observed by other methods. It also afford a capability to process large quantities of data.

The implementation of image processing technique to study of slug flow characteristics in vertical pipe has been studied by Mayor et al. **[14]**. MATLAB software was used to analyze the binary images and produced data analysis of Taylor bubble length, slug length, and Taylor bubble velocity which considering the associated uncertainty. Pujara et al. **[15]** conducted that image processing technique could be applied for void fraction measurement which resulted void fraction, bubble frequency, number of bubble in particular time duration, and average bubble length. MATLAB is commonly used for the study of moving object detection and tracking. **[16, 17, 18]**.

Slug flow is characterized by the presence of plug flow - which the presence of aerated bubble in slug flow as differentiator. This paper is focussing on the characteristics study of plug flow as an initial trait before the slug flow. The main goal of this work is to investigate plug flow topology concerning an accurate image analysis technique. This present work is related with visualization result by Dinaryanto **[19]** and Widarmiko **[20]** conducted plug and slug flow characteristics in 26 mm horizontal pipe. Those previous data denoted the result of manually flow visualization data, flow topology, and liquid hold-up using signal processing CECM that validated within this work. A good agreement between laboratory experiment and image processing data was obtained

2. Experimental Methods and Facility

A schematic layout of the experimental apparatus is shown in **Figure 1**. The facilities that used are located in Laboratory of Fluid Mechanics, Mechanical and Industrial Engineering Department, Universitas Gadjah Mada.

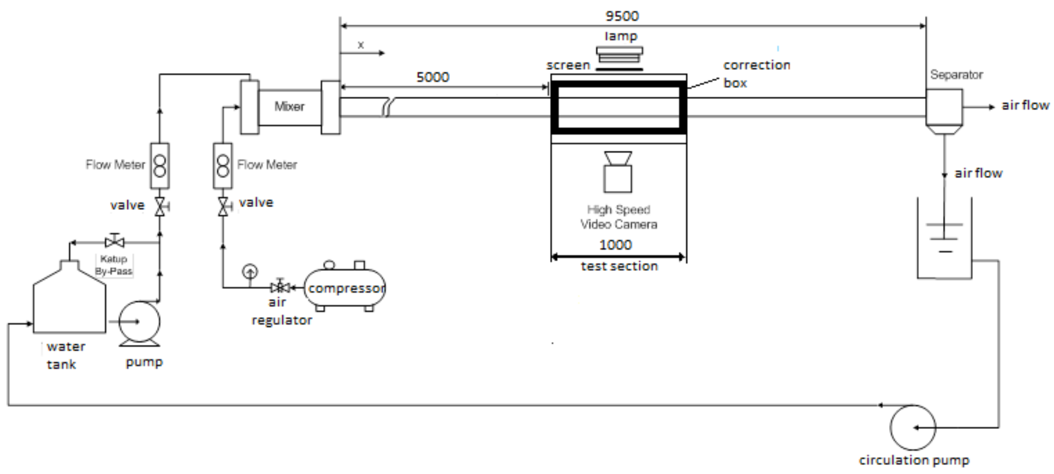

Figure 1. Schematic view of the experimental apparatus

The experiment was performed in a transparent acrylic pipe with 26 mm internal diameter (9.5 m long). Water and air, which were mixed by porous mixer, flowed adiabatically as a co-current two-phase flow along the pipe. It was used of 5 m length of pipe located before the test section to ensure fully developed flow and 1 m length of pipe as visualization test section zone. Hence, the motion of Elongated bubble and interfacial behavior of plug and slug flow could be well-observed.

Series of images were recorded using Canon Power Shot S100 video camera with resolution of 640 pixels width and 480 pixels height. The recording speed was 120 frame per seconds (fps). A rectangular transparent acrylic box (1.2 m long) used as correction box in order to reduce image distortion. This box was filled with water (1.33 of refractive indices), close to the refractive indices of acrylic (1.49). There were used of several matrix data of J_L (superficial velocity of liquid) from 0.25 – 1.13 m/s and J_G (superficial velocity of gas) from 0.12 - 0.51 m/s. The cases adapted from Mandhane (1974) flow pattern map of plug flow.

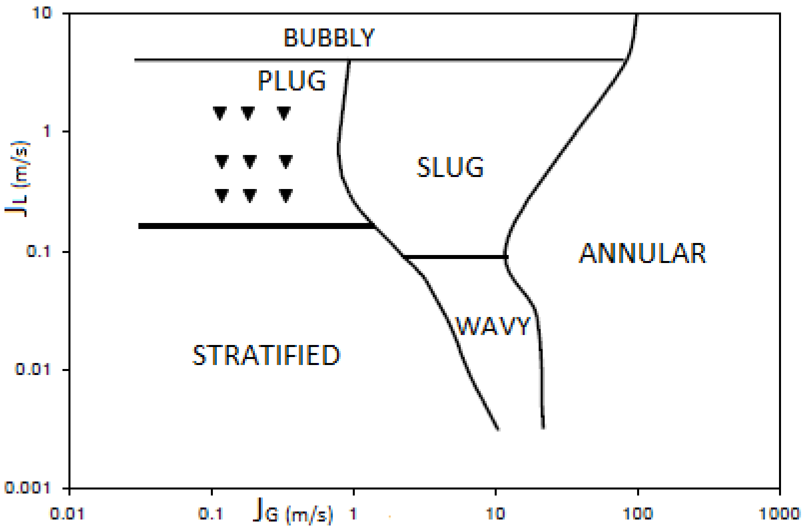

Figure 2. Schematic view of matrix data based on Mandhane (1974) flow pattern map

3. Digital Image Processing Technique

The recorded video were converted to be ‘avi’ file format of videos by Media Converter software for the proper format of the next step. Moreover, these were extracted into sequences of images by Virtual Dub software. As the results, 3600 frames of images were produced by this extraction from each 2 minutes video. Series of images then were processed by MATLAB 7 (R2010a) codes for the digital image processing technique. For the digital image processing, each image frame was treated as a matrix data (row and column processing) in pixel unit. The present technique optimized internal MATLAB’s function as an important way for image treatment. This work was used thresholding method to find binary image.

Consider that the analysis of many sequences of images would cause RAM (random access memory) shortness problems, sample of images were implemented. Before the image analysis, a number of image frames were selected as images sample. Each sample was contained of one or more elongated bubble while one video was splatted to be 3 samples. Thus, a statistical calculation through those samples was applied.

A sequential procedure was implemented for processing each image frame. This procedure is briefly described below.

3,1 Image loading
Each image frames was loaded as 8 bits of RGB (red, green, blue) image with ‘jpeg’ file format. A ‘sprintf’ command in MATLAB made possible to process sequence of image in a looping file by treated them as spring-files. **(Figure 3a)**

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3.2 Image conditioning

The raw image loaded were not always in the best condition. Hence, a special treatment was needed to optimize the best condition for image loaded. Based on the initial condition, the rotation of images was done for several cases due to the images orientation. It would ensure best input for the next steps.

3.3 Image conversion to grayscale

Each frame was converted from RGB to grayscale. The output image had 256 grey level ranging from 0 (black) – 255 (white) pixels. It was used of *'rgb2gray'* rather than other methods. **(Figure 3b)**

3.4 Image cropping

The grayscale images then were cropped into desired size in order to be intensively analyzed in certain region. The images were cropped based on how information could be obtained. **(Figure 4a)**

3.5 Background subtraction

In order to give the best condition of images, a new background was also prepared from the image complement of each frame. First, a MATLAB internal function of '*imcomplement*' produced complement images of grayscale cropping images. Then, through the *'imopen'* function, new background of images were automatically made. This function were combined with morphological operation *'strel'*. Through this function, there were more evenly intensity of images. Hence, subtraction of the complement image and background images was shown in **figure 4b.**

3.6 Image filtering

Several filtering methods such as Median filtering and Wiener Filtering were implemented in order to attenuate and reduce the image noise. For Median filtering, each output pixel is determined by the median value of the neighborhood pixels. Wiener filtering is a type of linear filtering which worked adaptively into the images by tailoring itself to the local image variance. The lowest level of image noise was resulted. However, a slight decrease in image sharpness occurs as the effect. **(Figure 4c)**

3.7 Image adjustment

For particular case, the luminosity intensity of images need to be increased by improve and level the contrast intensity. This method were not implemented for enough level of intensity images. (**Figure 4d**)

3.8 Image conversion to binary mode

Threshold value was required for grayscale image conversion to binary mode. In this procedure, grayscale images were converted to black and white image based on threshold value. Each pixels corresponded to be 1 (white) for higher value than threshold value, otherwise for the opposite will be value of 0 (black). There were two ways to determine threshold value. First, *'graythresh'* which used Otsu's method. This procedure was worked by minimize the interclass variance of the threshold black and white pixels. Second, by set manually the threshold value. As the results, sequences of binary images then would be the major objects to be quantitatively analysed for the next data analysis.

3.9 Data Analysis

Sequences of binary image then be analysed to find important flow parameter data. This quantitative analysis that implemented were based on object tracking algorithm combined with statistical methods.

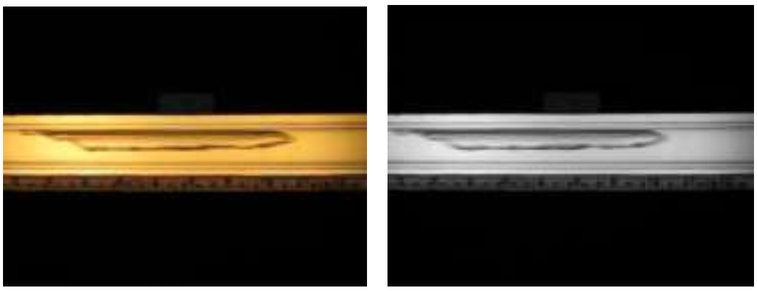


Figure 3. Elongated bubble (a) Original RGB image (b) Grayscale image (J_G=0.51 m/s and J_L=0.77 m/s)

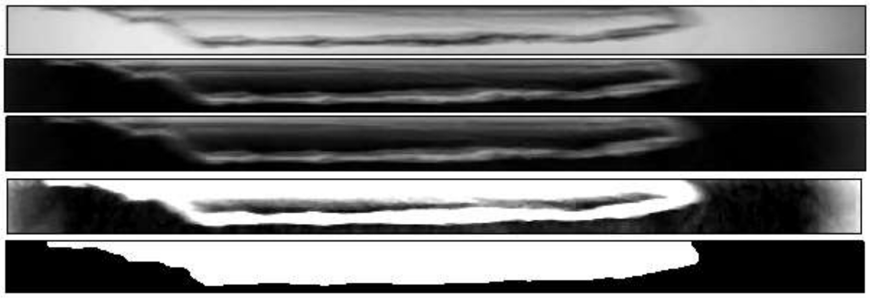


Figure 4. The following procedure of image processing technique: (a) Result of cropped image (b) after background subtraction (c) after image filtering (d) view of adjusted image (e) after conversion to binary mode. (J_G=0.51 m/s and J_L=0.77 m/s)

4. Result and Discussion

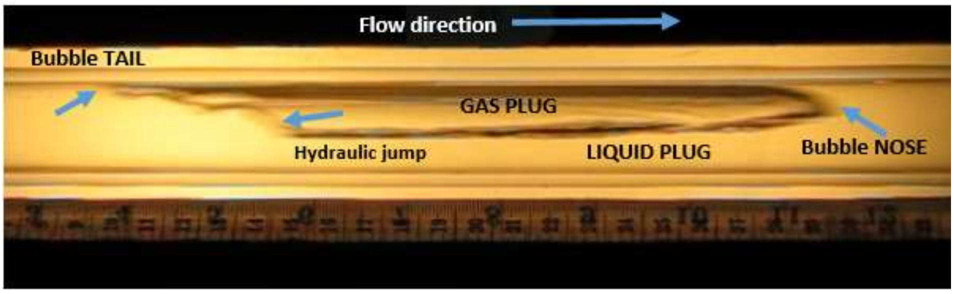


Figure 5. Visualization result of gas-liquid plug flow
(J_G=0.51 m/s and J_L=0.77 m/s)

4.1 Interfacial behaviour

An image processing technique could be used to point a better interface. The use of *'bwperim'* was to explicate object perimeter that showed a prominent interface between gas and liquid. The other function of image labelling also provided a clear phase boundary – by distinguishing the colour between gas and liquid in slug/plug flow. **(Figure 6)**

This technique decisively characterized the two-phase flow. The important slug/plug flow parameter, such as bubble tail and nose, hydraulic jump, and gas plug dynamics could be depth observed after clearly distinguishable interface. Thus, this technique will be useful for deep investigation of slug/plug flow mechanism of formation.

Figure 6. (a) binary image (b) perimeter of image (c) after image labelling
(J_G=0.51 m/s and J_L=0.77 m/s)

Table 1 and 2 show the visualization result of bubble nose and tail shape of the plug flow. For instances, the increase of J_G and J_L value cause different contour of bubble nose and tail. Theoretically the different combination of J_G and J_L induces different length of the elongated bubble, stated that the increase of J_G (in the same value of J_L) leads longer gas-plug. In the other hand, the increase of J_L (in the same value of J_G) resulted shorter gas-plug. It is demonstrated by this table that the binarization methods in image processing technique can be used as a method of approach – to represent the visualization data. The facts of different contour may influence a work of mathematical models development that give deep information about slug and or plug flow mechanism of formation. Furthermore, image processing technique also be possible to determine the length of elongated bubble.

Table 1. Comparison between nose contour (picture-binary) for each measurement

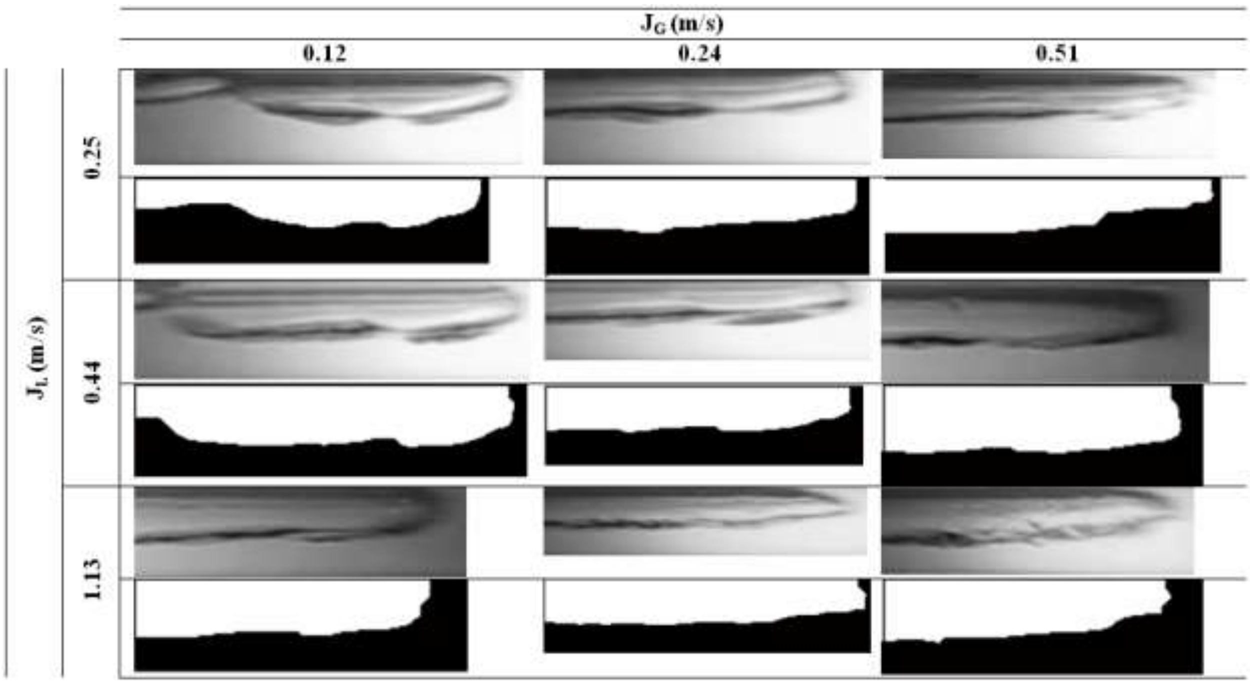
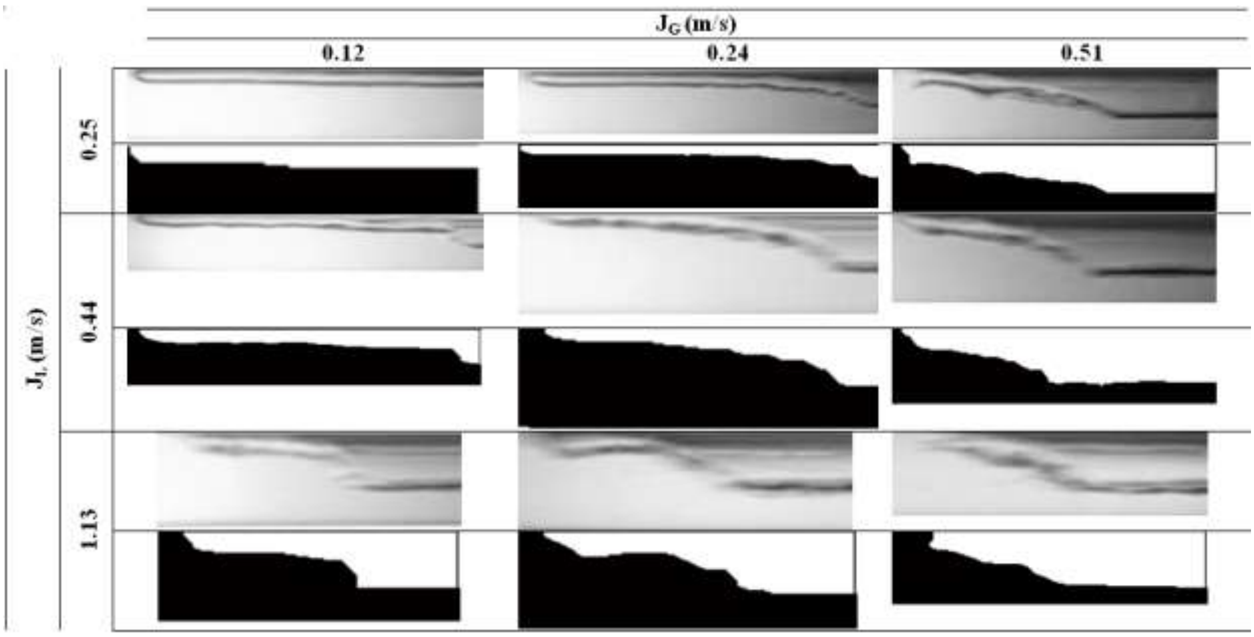


Table 2. Comparison between tail contour (picture-binary) for each measurement



4.2 Liquid film thickness

Each image were divided into four selected points of thin column. The purpose was to obtain a local analysis. First, the image size was measured. It resulted a matrix of [rows column] matrix that stated the number of rows and columns. After that, the division range from x/L=1/640 (1^{st} pixel column) until x/L=1 (640^{th} pixels column) was appointed. The purpose was to find liquid film thickness and gas-plug thickness. **Figure 7a** represents the four division zone of the image.

Each divided zone of column had 1 pixel column of width size and as-same-as the number of image row as image height. The object tracking algorithm ensured the obtainment of the lowest point of gas-plug along a column, definite as the maximum of white object point in a column. From this method, the result of gas-bubble thickness (t_G) could be determined. The top coordinate set as the reference point. Thus, by the subtraction of total rows (column height) plus one pixel, thru gas-bubble thickness, the liquid film thickness (δ) could be obtained. (**Figure 7b)**. The importance of 1 pixel addition to column height (h) was related to the initial reference position. If no addition, the exact coordinate of the interface could not be exactly determined (the result would resulted at odds 1 pixel). The exact calculation of t_G actually showed the interface between gas and liquid. Remember that the function of *'find'* in MATLAB provided a result of maximum and minimum position of white-pixel object tracking. Gas-bubble thickness was a product of maximum find of tracking. The value of h and t_G is in pixels unit and by multiple with calibration value (pixel to mm), the value of δ can be obtained in mm-unit. The relationship between bubble-gas thickness, height, and liquid thickness is shown in equation:

$$\delta = [(h+1) - t_G] \times calibration \quad (1)$$

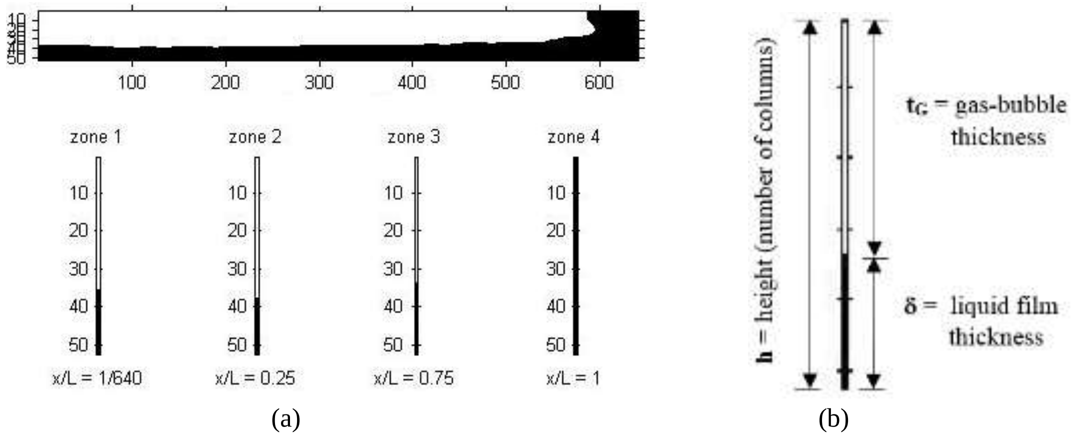


Figure 7. (a) Illustration of the image division (for 1st, 160th, 480th, 640th pixels column) (b) Representation of liquid film thickness measurement method

Figure 8 represents the result of liquid film thickness measurement in one of three sample (in one matrix data), containing two-elongated bubble in 0.9 s time. In this figure, the liquid film thickness data also shows the characteristics of the bubble contour. This data is based on specific reference point that had been passed by the objects for a certain time. From this data, the formation of plug flow, such as bubble nose, tail, and conditions with no presence of bubble is able to be recognized **(figure 9a)**. For the point of x/L=1, there were a little noise that may be caused by the imperfection in thresholding of binarization process and the shape fluctuation so that it has a little different contour.

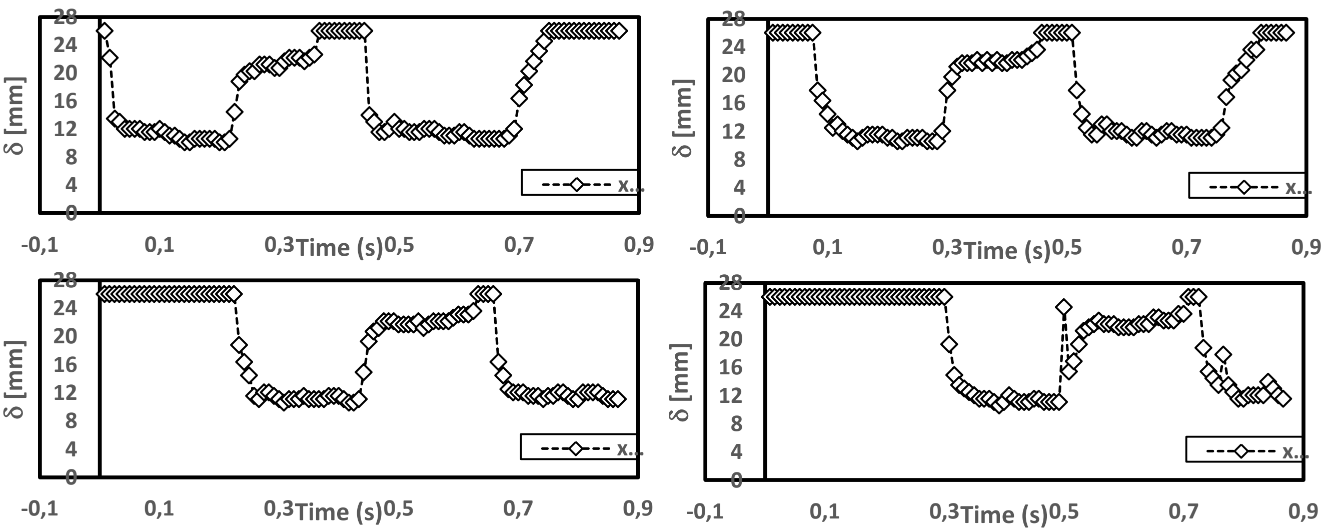


Figure 8. Liquid film thickness of two elongated bubble in a sample of plug flow

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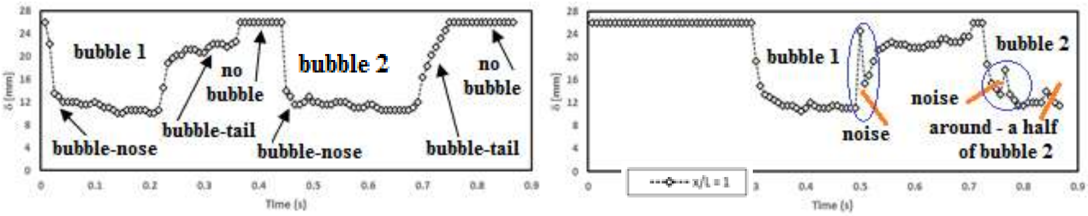
(J_G = 0.24 m/s and J_L=0.44 m/s)



(a) (b)

Figure 9. (a) Representation of bubble characteristics from the liquid film thickness data (x/L=1/640) ; (b) Representation of noise in fourth data (x/L=1) (J_G = 0.24 m/s and J_L=0.44 m/s)

Furthermore, the data of liquid film thickness can be used as input data for liquid hold-up and or void fraction calculation. It also can be an alternative method to find gas-bubble velocity by consider time difference (image frames needed) and distance between two reference points.

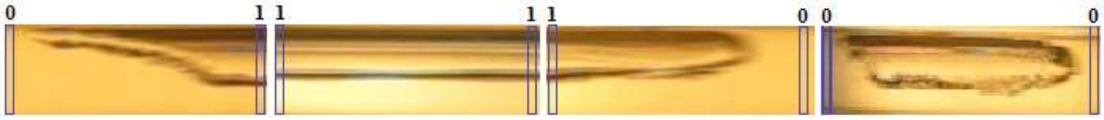
4.3 Elongated bubble velocity

Due to the elongated bubble flow type through image frames, there were two reference points, divided as *"inlet"* (1st pixel column) and *"outlet"* (640th pixel column) zone of the image frames. The presence of bubble was addressed as 1, otherwise recognized as 0 condition. To determine the elongated bubble velocity, it was used 3 cases of algorithm:

(a) *the use of tail velocity* – when the movement of bubble nose could not be obtained but difference coordinate of bubble tail could be measured. By this algorithm, a 'minimum find' of object tracking were used. (inlet=0 and outlet=1). **(Figure 10a)**

(b) *no velocity obtained* – velocity was neglected because of no presence of parameter point. This case was implemented both if no object (bubble) in image frame and for long gas-plug bubble (no striking movement of the objects). So, the assumption of inlet=0 and outlet=0 (for no bubble and short length of elongated bubble in middle of frame) or inlet=1 and outlet=1 (for long bubble were obtained). **(Figure 10b and 10d)**

(c) *the use of nose velocity* – when the movement of bubble nose could be obtained, by the difference of bubble nose coordinate. By this algorithm, a 'maximum find' of object tracking were used. (inlet=1 and outlet=0). **(Figure 10c)**



(a) (b) (c) (d)

Figure 10. Illustrations of the cases of algorithm for bubble flow type

In order to determine the translational bubble velocity, Van hout et.al **[10]** proposed an equation which divide the coordinate difference of bubble entering the field view of camera (pix1) and leaving it (pix2) by number of frame elapsed between bubble entering and leaving the field view of the camera (Δ_{frames}) . The "*pixelsize*" is a calibration procedure (mm/pixel) and involving the camera frame rate (60 fps).

$$U_{tr} = \frac{|pix_1 - pix_2|}{\Delta_{frames}}\ pixelsize\ (60\ fps) \quad (2)$$

The equation then adopted for this work by the use of 2 frames as Δ_{frames} for each data, 120 fps – camera frame rate, and calibration from pixel to mm. This calculation applies for nose and or tail velocity calculation. The calculation of Ug [m/s] is defined as follows:

$$U_G = \frac{|x_{final} - x_{initial}|}{\Delta_{frames}} \times calibration \times fps \times \frac{1}{1000}\ [m/s] \quad (3)$$

The value of U_G are processed by statistical method of mean to find an average value of each gas-bubble velocity in one sample of each matrix data. This equation is given by:

$$U_G = \frac{\sum_{i=1}^{n} U_{G,i}}{n} \quad (4)$$

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Figure 11 presents the influence of J_L and J_G toward gas-bubble velocity. The increase of J_G (in the same value of J_L) leads higher gas-bubble velocity. Otherwise, the increase of J_L (in the same value of J_G) also obtained a higher U_G. This happens due to the liquid plug flow containing gas-bubble. The gas-bubble velocity (U_G) then correlated with Franca & Lahey **[21]** (based on the drift-flux model). It shows a correlation to find velocity of gas-bubble by knowing the superficial velocity of mixture (J_m). For plug flow, the coefficient of C_o = 1 and v_{Gj} = 0.16. The correlation is defined as follows:

$$U_G = C_o J_m + v_{Gj} \qquad (5)$$

A similar configuration is obtained. The bubble-gas velocity data has a good agreement with Franca & Lahey **(figure 10a)** by the suitable graph trendline and a good data range. This data also has a good agreement with the physical experiment data that has done by Widarmiko (2012). Hence, it concluded that the image processing technique is accurate enough to investigate the gas-bubble velocity.

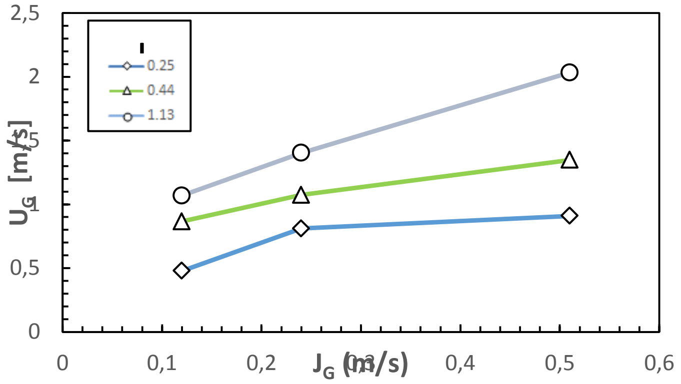
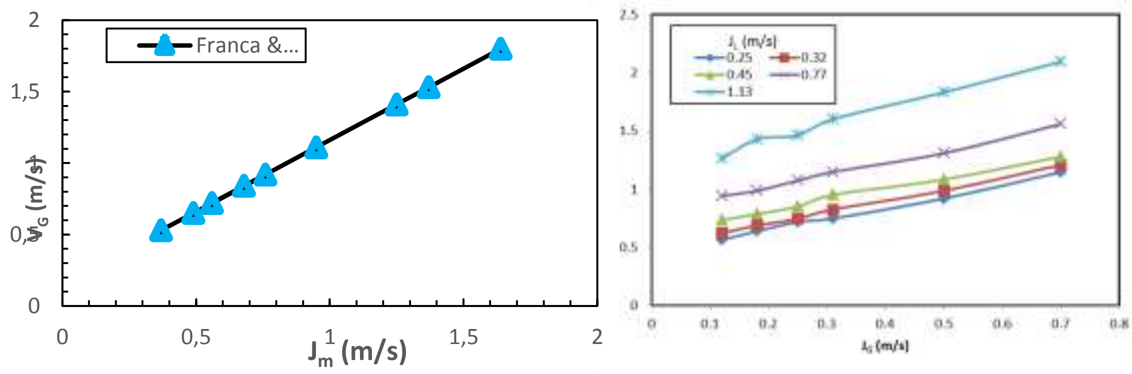


Figure 11. Relationship between gas-bubble velocity with superficial velocity of gas and liquid



(a) (b)

Figure 12. Average velocity of plug flow (a) Franca & Lahey (1992) (b) Widarmiko (2012)

5. Conclusion

An image processing technique has been developed to study the gas-liquid plug flow characteristics in a horizontal pipe. This technique shows a clear interphase between gas and liquid phase. Hence, an apparent interfacial behavior could be determined through this technique. It is useful to recognize visualization parameters including formation of plug flow. The identification of bubble nose and tail contour was presented for each combination of superficial velocity of gas (J_G) and liquid (J_L). The important flow parameters such as gas-bubble velocity and the liquid film thickness are also reported. It was found that the increase of J_G and J_L would also increase the gas-bubble velocity. By comparing the results with other previous experiments, it is concluded that the image processing technique is an accurate and useful methods to describe the plug flow characteristics.

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