The Implementation of Image Processing Technique to Determine the Interfacial Behavior of Gas-Liquid Wavy Two-Phase Flow In A Horizontal Pipe

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Abstract

Two-phase flow phenomenon in pipelines is frequently experienced in the petroleum, chemical and nuclear industries. In-depth knowledge of this phenomenon is highly necessary in order to get better information about the effect to the system. The complexity behavior of flow pattern in the two-phase flow was studied by many researchers and they had proposed various models to figure-out the phenomenon, which were different from each other. Hence, the validity is needed to get more valid result and better understanding. There are several flow patterns of two-phase flow in horizontal pipe; one of them is stratified gas-liquid two-phase flow pattern.This experiment was proposed to determine the interfacial behavior of gas-liquid wavy flow in horizontal pipe using digital image processing technique, and also gave more database in stratified gas-liquid two-phase flow. From this experiment, we could understand the characteristics of stratified gas-liquid two-phase flow by the term of two-phase flow topology and understand the interfacial behavior of stratified gas-liquid wavy two-phase flow using digital image processing technique. Stratified gas-liquid two-phase flow pattern was simulated with well-arranged experiment apparatus set up in Fluid Mechanics Laboratory, Mechanical and Industrial Engineering Department, Faculty of Engineering UGM. Transparent acrylic horizontal pipe with internal diameter 26 mm was used in this experiment, therefore the interfacial behavior could be observed. Pipe length before the visualization test section was 5 m to ensure fully developed stratified gas-liquid two-phase flow and the visualization test section pipe length was 1 m. Water and air were used as liquid fluids and gas fluids moving cocurrently along it. There were 24 matrix data variations of J_L (water superficial velocity) and J_G (air superficial velocity) with the range 0.016 m/s to 0.092 m/s for J_L and 1.02 m/s to 3.77 m/s for J_G. Stratified gas-liquid two-phase flow characteristics were observed by high speed video camera. The flow was recorded on video and the images were digitized on a computer. Digital image processing techniques were then used to perform quantitative analysis and the result would be used to evaluate the existing data. MATLAB was used as tool for digital image processing. From the image data, the distribution of liquid film thickness from each matrix data variation was obtained. Then, the distribution liquid film thickness data was used to get information about probability distribution function of a liquid hold-up, power spectral density, and probability distribution of a liquid hold-up. The result was used to study the interfacial behavior of the stratified gas-liquid two-phase flow and used to validate the previous experiment result.

Keywords: Stratified gas-liquid two-phase flow, Visual characterization, Liquid hold-up, Digital image processing.

Introduction

Two-phase flow phenomenon in pipelines is frequently experienced in the petroleum, chemical and nuclear industries. In-depth knowledge of these phenomenon is highly necessary in order to get better information about the effect to the pipelines system. The complexity behavior of flow pattern in the two-phase flow was studied by many researchers and they had proposed various models to figure-out the phenomenon, which were different from each other. Hence, the validity is needed to get valid result and better understanding.

There are several flow patterns of two-phase flow in horizontal pipe. One of them is stratified two-phase flow pattern, which is characterized by the liquid moving along the bottom of the flow channel and the gas cocurrently above it. When the gas velocity is sufficiently low, the gas-liquid interface appears undisturbed. This flow structure is recognized in various horizontal flow pattern maps by the definition of a stratified smooth flow pattern. However, as the gas velocity is increased in stratified flow, waves are formed on the gas-liquid interface, giving a stratified wavy flow pattern. Corresponding author: [1]E-mail:hadiyan.y.kuntoro@gmail.com; [2]E-mail:

deendarlianto@ugm.ac.idResearchers who had been conducted experiment of gas-liquid two-phase flow pattern in horizontal pipe among others Mandhane et al [1], Taitel and Dukler [2], Spedding and Nguyen [3], Spedding and Spence [4]. While, researchers who had been focus investigated in stratified flow behavior experiment among others Lockhart and Martinelli [5], Kawaji et al [6], Franca and Lahey [7], and Vlachos et al [8].

Another flow pattern is slug two-phase flow pattern. This kind of flow can triggers damage in pipe applications, such as corrosion, abrasion, and blasting pipe. Those incident happens because fluctuation of local pressure different that is caused by friction between liquid slug and upper inside pipe, liquid slug and lower inside pipe, and slip between phase. Therefore, slug flow pattern is undesirable in pipelines, and the flow is maintained at stratified flow condition for safety reason.

Many methods have been developed to determine the interfacial behavior of flow pattern that occur in pipelines, such as conductance method were conducted by Kang and Kim [9], Shi and Kocamustafaogullari [10]. Fukano [11] developed the conductance method to be CECM (Constant Electric Current Method) and used to study the time varying thickness liquid film flowing with high speed gas flow. Yuichi Murai et al [12] investigated about the moving interfaces in gas-liquid two-phase flow by using ultrasonic detection.

Another method is by visual observation using digital image processing technique. Gopal and Jepson [13] developed the digital image analysis techniques for the study of velocity and void profiles in slug flow. Mayor et al [14] carried out the implementation of digital image processing technique for study of gas-liquid slug flow along vertical pipes. Montoya et al [15] performed the digital image processing for study of the interfacial behavior of the countercurrent gas-liquid two-phase flow in a hot leg of a PWR. For horizontal annuli case, Ozbayoglu and Yuksel [16] analysed the gas-liquid behavior with image processing techniques, but not focused on the stratified two-phase flow pattern. Recently, Amaral et al [17] investigated using image processing techniques in horizontal two-phase slug flows.

Meanwhile, the implementation of digital image processing technique for study in stratified flow still uncommon, so that, the more research by this method is needed in order to get in-depth understanding of stratified two-phase flow. In the present study, flow visualization techniques are developed to conduct a detailed analysis of the local characteristics of stratified flow. The flow was recorded on video and the images were digitized on a computer. Digital image processing techniques were then used to perform quantitative analysis.

From previous elucidation, in-depth research was needed in stratified two-phase flow pattern due to the important role in industrial practice. Also, in scientific view, the lack of database and rarely investigation using digital image processing technique was the motivation of this research. In order to get thorough knowledge about the phenomena and tried to validate the earlier experiment using different technique, the research was done. This experiment was proposed to determine the interfacial behavior of gas-liquid wavy flow in horizontal pipe using digital image processing technique, and also gave more databases in stratified flow case.

Experimental facility and procedures

Location

The experiment conducted in Fluid Mechanics Laboratory, Mechanical and Industrial Engineering Department, Faculty of Engineering Universitas Gadjah Mada.

Materials Research

Water and air were used as liquid fluids and gas fluids moving cocurrently along it. The specification of each fluids were:

Liquid fluids	: water
Gas fluids	: air
ρ water	: 996 kg/m^3
ρ air	: 1.163 kg/m^3
μ water	: 0.799 x 10^{-3} N.s/m^2
μ air	: 1.85 x 10^{-5} N.s/m^2
υ water	: 0.802 x 10^{-6} m^2/s
υ air	: 1.597 x 10^{-5} m^2/s

Experiment apparatus

Schematic diagram of apparatus is shown in Figure 1. In order to ensure the outlet mix flow of air-water becomes stratified two-phase flow, separated inlet by a flat plate was used as mixer in air-water mixing process. Transparent acrylic horizontal pipe with internal diameter 26 mm was used in this experiment, so that the interfacial behavior could be observed. Pipe length before the visualization test section was 5 m to ensure the fully developed stratified two-phase flow. The visualization test section pipe length was 1 m. Stratified gas-liquid two-phase flow characteristics were observed by high speed video camera. Canon Power Shot S100 was used as the high speed video camera with shutter speed 120 fps and 640 x 480 pixel resolution. LED lamp was used as the light source. The flow was recorded on video for 30 s each matrix data and the images were digitized on a computer.

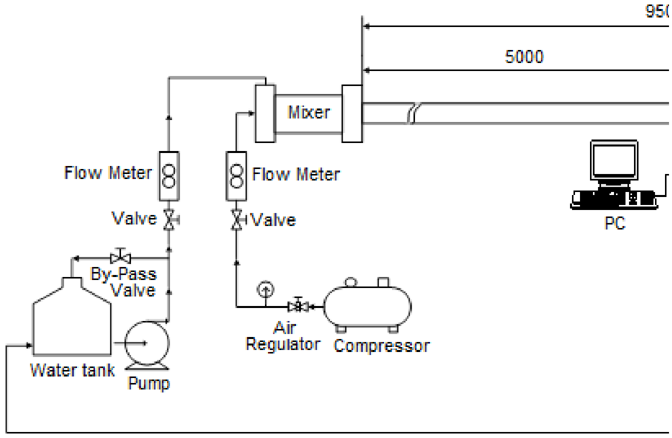


Figure 1. Experiment apparatus

Experiment procedures

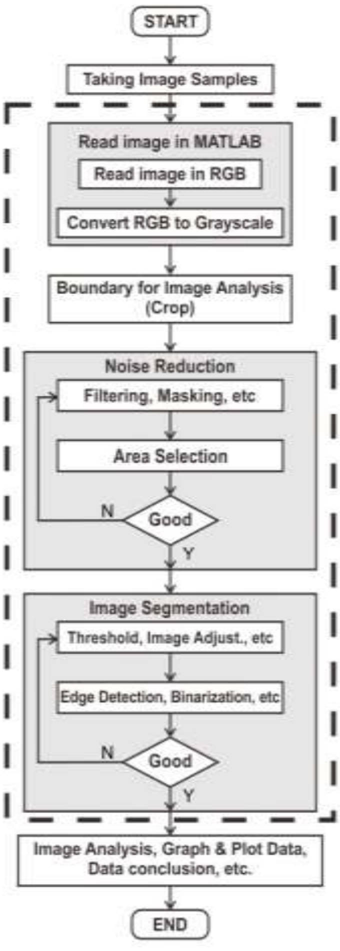
Experiment was carried out by the following standard operational procedures: **(a)** Work condition measurement is carried out by measure the temperature of water and ambient air, **(b)** Fill the inlet tank with water for the first start until 75% of inlet tank capacity. Before fill the inlet tank, the water must be filter using porous media to avoid dirt, **(c)** Close the air valve toward mixer to prevent water entry the air flowmeter, **(d)** Close all valves toward water flowmeter and fully open by-pass valve of main pump, **(e)** Turn on compressor to generate pressure in order to prevent water entry the air flowmeter, **(f)** Turn on main pump and circulation pump, **(g)** Open the air flowmeter valve gradually until certain discharge is attained, then calculate and note the air superficial velocity (J_G), **(h)** By maintain the air superficial velocity (J_G) constant, open the water valve gradually until stratified flow pattern is reached, then measure the water discharge. Calculate and note the water superficial velocity (J_L), **(i)** In specific J_G and J_L, the flow is recorded using high speed video camera 120 fps with 640 x 480 pixel resolution for 30 s. Then, vary the J_G - J_L and record again. The variation of J_G - J_L can be seen in Table 1, **(j)** Perform the quantitative analysis using digital image processing technique on computer from digitized image of the recorded image by high speed video camera.

Research matrix data

There were 24 matrix data variations of J_L (water superficial velocity) and J_G (air superficial velocity) with the range 0.016 m/s to 0.092 m/s for J_L, and 1.02 m/s to 3.77 m/s for J_G. Research matrix data of stratified gas-liquid two-phase flow was retrieved by refers to Mandhane [1] flow pattern map of stratified smooth and wavy region. Table 1 shows the variation of research matrix data with numbering from 1 to 24.

Table 1. Research matrix data

	J_L = 0.016 m/s	J_L = 0.031 m/s	J_L = 0.047 m/s	J_L = 0.063 m/s	J_L = 0.077 m/s	J_L = 0.092 m/s
J_G = 1.02 m/s	1	2	3	4	5	6
J_G = 1.88 m/s	7	8	9	10	11	12
J_G = 2.83 m/s	13	14	15	16	17	18
J_G = 3.77 m/s	19	20	21	22	23	24



Quantitative analysis

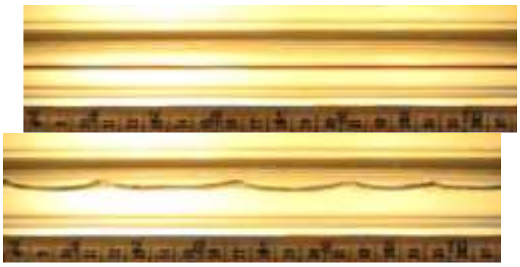
Recorded images by high speed video camera were transferred to the computer in the format of video file. The individual image was obtained by the extraction process of video file. The mov video file format was converted to avi video file format using video converter software. Then, the avi video file format was extracted to be frame by frame images in order to perform the digital image processing technique using MATLAB. Specifically, Mayor et al [14], Montoya et al [15], Ozbayoglu and Yuksel [16], and Amaral et al [17] used MATLAB as tool for digital image processing. From the images data, the distribution of liquid film thickness of each matrix data variation were obtained and were used to find out the distribution of the liquid hold-up, wave velocity, and wave frequency.

Image processing technique

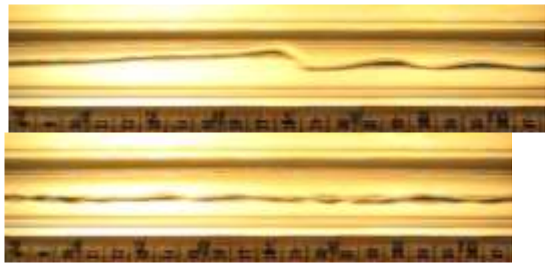
here were sequential processes to obtain the desired data from the recorded images (Figure 2). The image processing concept was to change the RGB images (from the recorded images) by means of sequential processes to binary images, that only contain two type value data, 0 for black and 1 for white. From the binary images, the distribution of liquid film thickness was obtained. The recorded images were processed using MATLAB through algorithm programs with this following sequences:

Taking image samples

High speed video camera recorded the stratified gas-liquid two-phase flow in the video file format, 640 x 480 pixel resolution for 30 s each matrix data. Then, the recorded video was extracted by the extraction software (VirtualDub) to obtain the sequential individual RGB image (Figure 3).



(a) Research matrix data number 1
(b) Research matrix data number 6



(c) Research matrix data number 12
(d) Research matrix data number 15

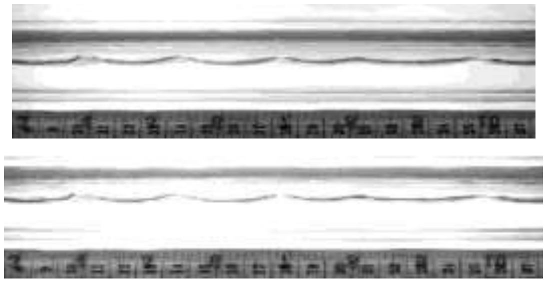
Figure 3. RGB image samples of research matrix data number (a) 1, (b) 6, (c) 12, (d) 15.

Read image

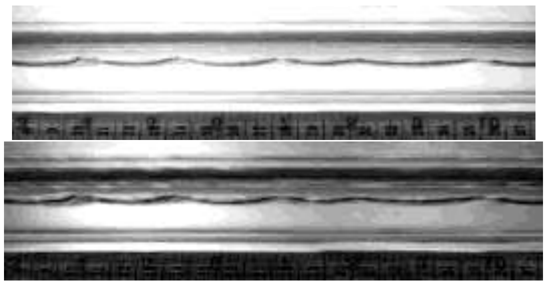
Each image were loaded in MATLAB as 8 bits RGB (red, green, and blue matrix layer) image format using imread function. [18 – 19].

Image conversion

Each image was converted to grayscale image format (1 matrix layer) by obtained the red layer in the RGB image, and used it as the new matrix layer (the R layer) rather than used the rgb2gray function in MATLAB. The grayscale image has 256 grey levels, ranging from 0 (black) to 255 (white). Ozbayoglu and Yuksel [16] performed this method also, but there was no detail explanation about the reason using this method. Figure 4 shows the comparison between grayscale image from 4 different conversion method.



(a) rgb2gray function method
(b) R layer separation method



(c) G layer separation method
(d) B layer separation method

Figure 4. (a) (b) (c) (d) The comparison between grayscale image from 4 different conversion method

Figure 4(b) shows the most contrast and less noise

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image rather than the others. This significant image result were suitable for further image processing because the objective was to obtained the gas-liquid interface (Figure 6) and eliminated the noise (the others form of image except the gas-liquid interface – Figure 8). The comparison in Figure 4 shows that the R layer separation method gave better image result rather than the rgb2gray function method.

Image cropping

Each image was cropped based on the region selection to obtain the inner diameter image of the pipe to get the desired data (Figure 8).

Noise reduction

The noise reduction process included image complement process (Figure 9) and image filtering process (Figure 10 – 11). In the image complement process, the image data value was reversed to the complement value, for example, 0 value reversed to 255 value, black color to white color and vice versa.
For the image filtering process, zero filtering (Figure 10) and average filtering (Figure 11) was used. The idea of average filtering was simply to replace each pixel value in an image with the average value of its neighbors, including itself. This had the effect of eliminating pixel values which were unrepresentative of their surroundings. The 3 x 3 neighbour pixel size was used in this filtering. This research also developed the new filtering method called zero filtering. The zero filtering concept was understood by replacing the non-interfacial gas-liquid image to be 0 value (black color). The plot technique should be performed first to separate the matrix image area between the gas-liquid interface and the noise.

Image segmentation

The image segmentation process included image contrast enhancement process (Figure 12), thresholding, binary image conversion (Figure 13), and morphological image process (Figure 14). Image contrast enhancement process was used to contrast the gas-liquid interface image with the background image. Thresholding and binary image conversion were done to convert the grayscale images into binary images. For morphological image process, skeletonize method was used. After all sequence processes were done, the skeletonize images were gathered.

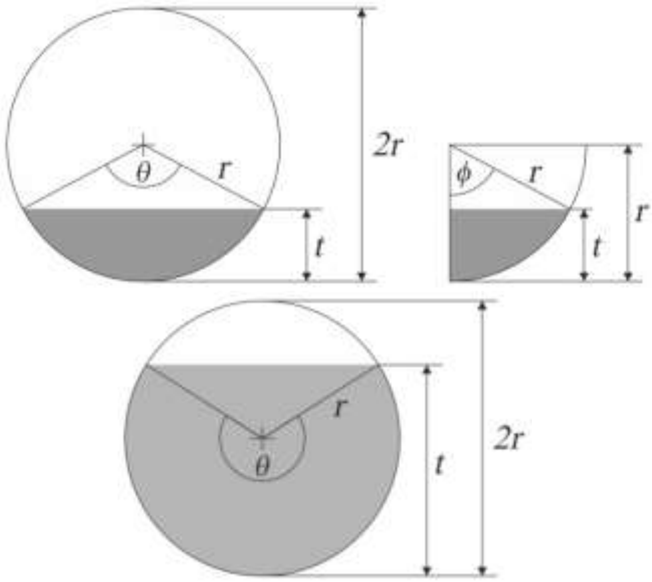
Data gathering

Image calibration

The calibration test was shown that 3 pixel in the images equal to 1 mm in real measurement. This calibration was important to know the real value of the liquid film thickness. The liquid film thickness data that was obtained from the images was in pixel units, then it converted to mm unit.

Data calculation

The high speed video camera recorded the longitudinal section of the horizontal pipe, so that the image information was in 2-D. Liquid hold-up known as the cross sectional area occupied by the liquid divided by the cross sectional area of the inner pipe. The plane curvature was used as the approach for calculating the liquid hold-up. The information of the liquid film thickness was used to calculate the liquid hold-up. The calculation of the cross sectional liquid area was approached by the circular segment area formula of the circle.



(a) For case t ≤ r
(b) trigonometry concept
(c) For case t > r

Figure 5. (a) (b) (c) The circular segment area approach to calculate the liquid hold-up
t = the liquid film thickness; r = radius of the inner pipe

Table 2. The formula

for $0 \le t \le$ r	for r < $t \le$ 2r
$\phi = \cos^{-1}\left(\frac{r-t}{r}\right)$ $\theta = 2 \times \phi$ $\theta = 2 \times \cos^{-1}\left(\frac{r-t}{r}\right)$	$\phi = \cos^{-1}\left(\frac{t-r}{r}\right)$ $\theta = 2\pi - (2 \times \phi)$ $\theta = 2\pi - \left[2 \times \cos^{-1}\left(\frac{r-t}{r}\right)\right]$

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for $0 \leq t \leq 2r$
$A_L = \frac{r^2}{2}(\theta - \sin\theta)$; $A_{circle} = \pi r^2$; $\eta = \frac{A_L}{A_{circle}}$
η = liquid hold-up; θ and ϕ are in radians; t and r are in mm; r = 13 mm in this research

Data plotting

The liquid hold-up data from the calculation of the liquid film thickness data using Table 2 formula was plotted on the graph and was analyzed; and the results were reported on results and discussion section.

Results and discussion

This research sucessfully recorded the stratified gas-liquid two-phase flow pattern in a horizontal pipe for 24 matrix data variations of J_L and J_G. The recorded image showed clearly the interfacial behaviour of stratified gas-liquid two-phase flow. Digital image processing technique was able to used to study the interfacial behavior of stratified gas-liquid two-phase flow pattern by the term of visual characteristics results and graph plot of the liquid hold-up distribution results, as follows:

Image processing

Figure 6 – 14 showed the digital image processing result of each process from RGB image (the recorded image) to skeletonize image (final result).

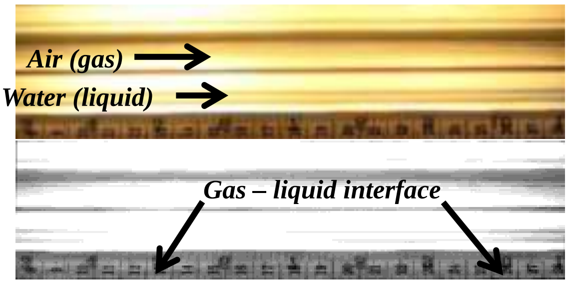


Figure 6. RGB image

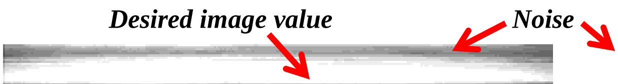


Figure 7.

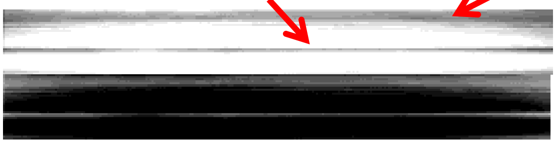


Figure 8. Image cropping result

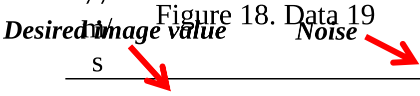


Figure 9. Image complement result

Figure 10. Image after zero filtering

Figure 11. Image after average filtering

Figure 12. Image after contrast enhancement process

Figure 14. Image after skeletonize process

The algorithm's program which was developed in this research was able to detect the gas-liquid interface of the recorded images and generated the average line of the gas-liquid interface. This line represented the gas-liquid interface of the stratified gas-liquid two-phase flow. The interfacial behavior of the stratified gas-liquid two-phase flow was studied from the reading of the average line using MATLAB.

Table 3. The samples of the skeletonize image result research matrix data no 1, 3, 7, 9, 13, 15, 19, and 21

	J_L = 0.016 m/s	J_L = 0.047 m/s
J_G = 1.02 m/s	 Figure 15. Data 1	 Figure 19. Data 3
J_G = 1.88 m/s	 Figure 16. Data 7	 Figure 20. Data 9
J_G = 2.83 m/s	 Figure 17. Data 13	 Figure 21. Data 15
J_G = 3.77 m/s	 Figure 18. Data 19	 Figure 22. Data 21

Table 3 showed the samples of the skeletonize image which were processed using image processing technique. Figures 15 – 18 showed the stratified smooth gas-liquid interfaces, while figures 19 – 22 showed the stratified wavy gas-liquid interfaces.

4.2 *Liquid hold-up distribution*

Table 4. Stratified smooth flow

	J_L = 0.016 m/s	
D	Liquid hold-up	probability

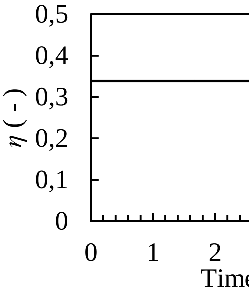
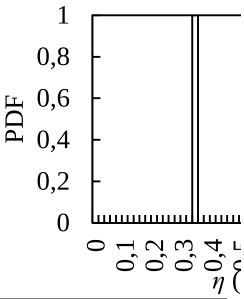
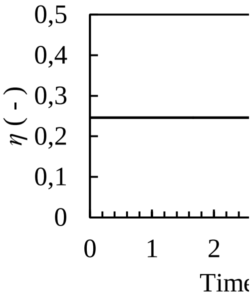
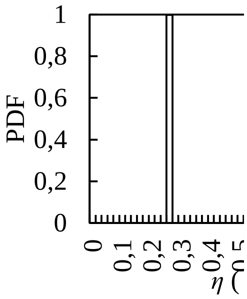
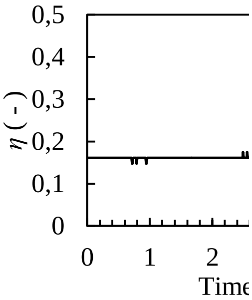
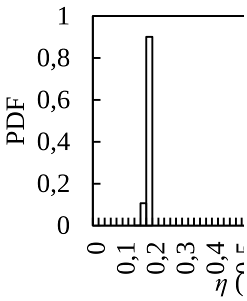
	at a	distribution	distribution function (PDF)
J_G = 1.02 m/s	1		
J_G = 1.88 m/s	7		
J_G = 2.83 m/s	13		

Table 5. Stratified wavy flow

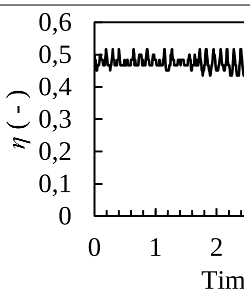
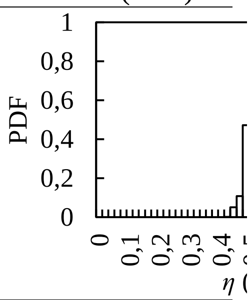
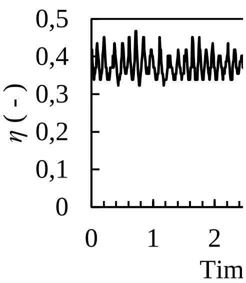
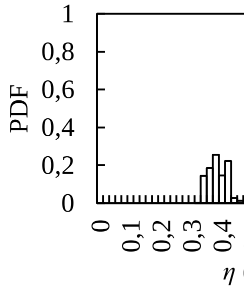
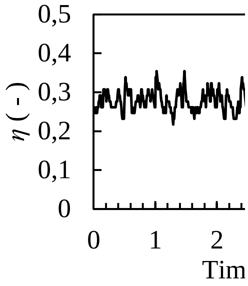
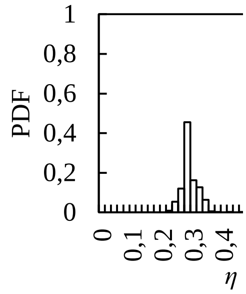
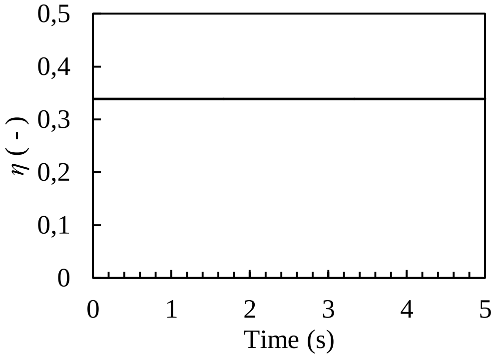
		J_L = 0.047 m/s	
	Data	Liquid hold-up distribution	probability distribution function (PDF)
J_G = 1.02 m/s	3		
J_G = 1.88 m/s	9		
J_G = 2.83 m/s	15		

Table 4 and Table 5 showed the difference between the stratified smooth flow and the stratified wavy flow. The stratified smooth flow showed the flat interface with the gathered distribution value of PDF (Table 4). On other hand, the stratified wavy flow showed the wavy interface form with the widened distribution value of PDF (Table 5).

Table 6. The comparison of the liquid hold-up distribution

	J_L = 0.016 m/s	J_L = 0.047 m/s	J_L = 0.092 m/s
J_G = 1.02 m/s	1	3	6
Figure	23	24	25



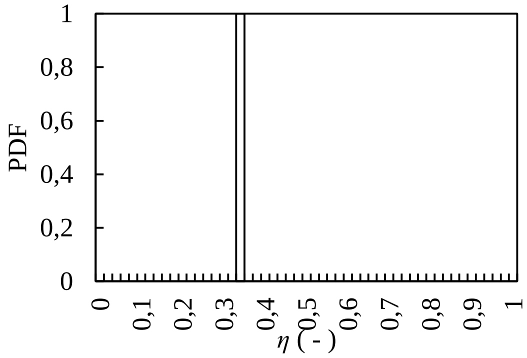


Figure 23. Liquid hold-up distribution and the probability distribution function (PDF) data 1

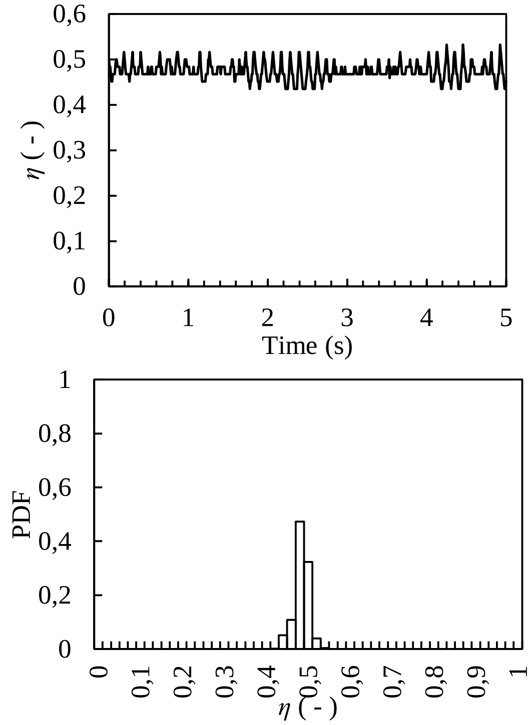


Figure 24. Liquid hold-up distribution and the probability distribution function (PDF) data 3

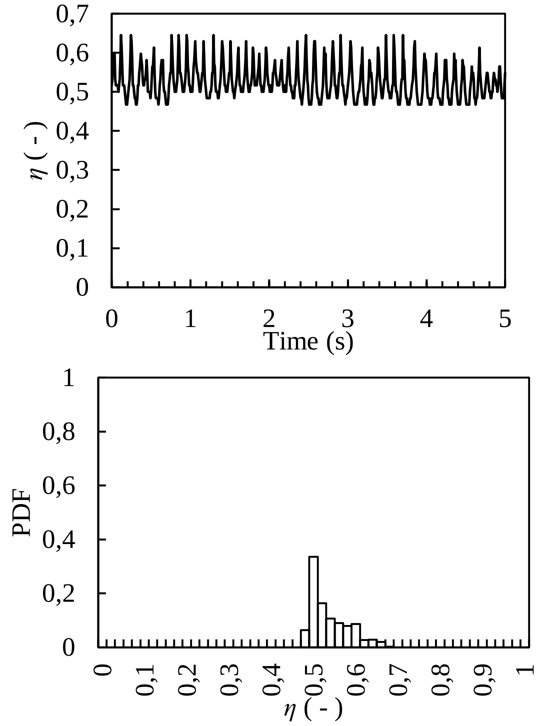
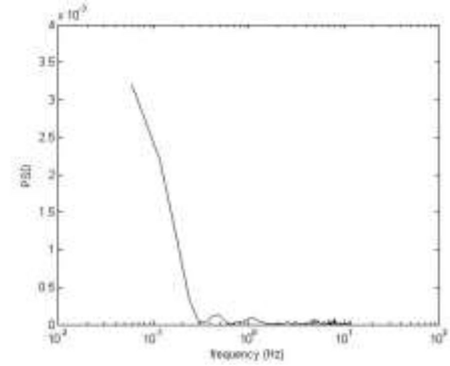
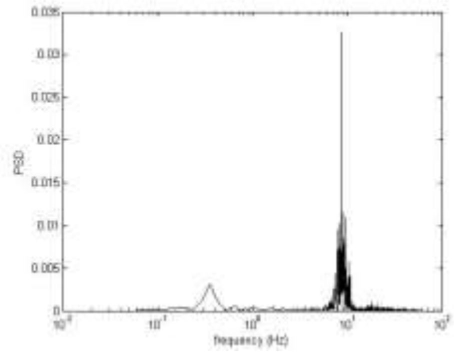


Figure 25. Liquid hold-up distribution and the probability distribution function (PDF) data 6

The liquid hold-up distribution value tended to drop if the air superficia while the water superficial velocity (J_L) was kept constant. In contrast, the liquid hold-up distribution value tended to rise if the water superficial velocity (J_L) had increased while the air superficial velocity (J_G) was kept constant. This was because the greater the value of J_G or J_L then the inertial forces that pushed the water or the air would be even greater.

4.3 *Power spectra density*





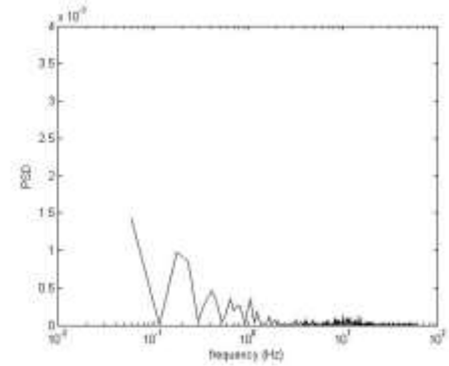


Figure 28. PSD data 13

Figure

Power Spectra Density (PSD) analysis showed that the wave frequency of stratified gas-liquid two-phase flow tended to increase if the water superficial velocity (J_L) had increased while the air superficial velocity (J_G) was kept constant. Meanwhile, the effects of changed in the air superficial velocity (J_G) was not significant to the wave frequency while the water superficial velocity (J_L) was kept constant.

Table 7. PSD's Comparison

	J_L = 0.016 m/s	J_L = 0.047 m/s
J_G = 1.02 m/s	Data 1	Data 3
J_G = 2.83 m/s	Data 13	

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