Journal of Fluids and Thermal Sciences
Volume 1, Issue 2, 11 June 2012, Pages 205-217

DIFFERENTIAL PRESSURE FLUCTUATION OF PLUG FLOW PATTERN GAS-LIQUID OF CO-CURRENT TWO PHASE FLOW IN A HORIZONTAL PIPE

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Abstract

Various measurement tools of statistic and chaos theory were applied to analyze two-phase flow plug. The experiments were carried out on an air-water flow in a horizontal pipe of i.d. 24 mm.

2010 Mathematics Subject Classification: 76T10.

Keywords: plug flow, differential pressure, probability density function, autocorrelation, power spectral density.

Received February 15, 2012

These measurement tools included mean, standard deviation, skewness, kurtosis, probability density function, autocorrelation function, and power spectral density function. The statistical analysis represents physical phenomenon that mean, standard deviation, skewness, and kurtosis change linearly to the superficial velocity. The autocorrelation function and power spectral density function analysis demonstrate that the random like differential pressure fluctuations characteristics of plug flow are chaotic in nature.

1. Introduction

The study of two-phase flows has a great significance for several technological applications. In particular, gas-liquid two-phase flows are often encountered in a wide range of industrial applications, such as condensers, evaporators, distillation towers, nuclear power plants, boilers, crude oil transportation, and chemical plants. Gas-liquid flow is not only the most common of the two-phase flows but also the most complex since it combines the characteristics of a deformable interface with those of a compressible phase. The transportation of gas and liquid in conducts can lead to several topological configurations called flow patterns or flow regimes [8].

The intermittent gas-liquid flow pattern observed in horizontal pipes is commonly subdivided into two sub regimes-slug flow and plug flow. Most of the studies in this field have dealt with slug flow so the characteristics of the plug flow are not well-defined. Plug flow (or also called *elongated bubble flow*) occurs at very low gas velocities and consists of elongated gas bubbles that move along the top of the pipe. In plug flow, the gas phase is present in the form of elongated bubbles transported in an aerated continuous liquid phase in the upper half of the tube (It is also referred as elongated bubble flow by Mandhane et al. [4]). Plug Flow has a special feature of the gas phase to form pockets of gas to the boundary between gas and liquid.

There are two quantities commonly monitored for the determination of the flow regimes: local pressure fluctuations and void fraction fluctuations. The examples of works that encouraged this direction are carried out by Jones and Zuber [2], Matsui [5] and Tutu [11]. The time series signals taken are statistically analyzed to obtain the information which can aid in the desired task. Typical statistical calculations that are used in those works are mean value of in the signal, standard deviation (SD), coefficient of skewness (CoS), power spectral density (PSD) of pressure signals, and probability density function (PDF) of a void fraction signal.

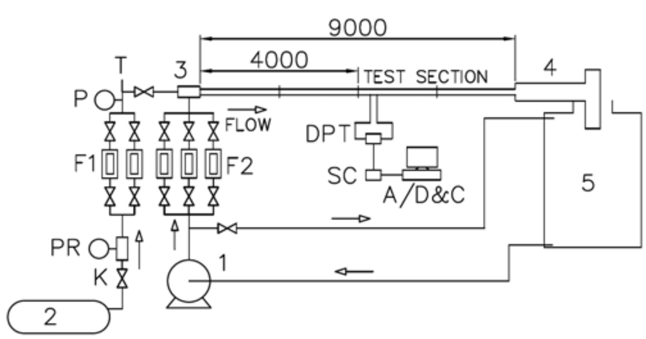
The effort to identify the two-phase flow patterns have been made in the past by using the objective sensor response-based methods. The patterns of the variations and fluctuations of local absolute and differential pressures [3, 6, 9, 13], for example, have been found to be strongly regime-dependent. They found that the statistical characteristics (power spectral density, probability density function, auto and cross-correlation functions) of the pressure fluctuations are particularly attractive for the flow pattern classification. It is due to the required sensors which are robust, inexpensive, and relatively well-developed, and are thus more likely to be applied in the industrial systems.

The characteristics of pressure and differential pressure signal have been used also as the criterion for the flow pattern recognition of multiphase flow [1, 3, 6, 9, 10, 15, 16, 17] focused on the fluctuation characteristics of these parameters.

This work shows how the statistical analysis of a local quantity provides reliable tools for plug flow identification, which can be given an immediate physical interpretation. In this paper, the signals are acquired with differential pressure sensor in plug flow of horizontal pipe.

2. Experiments Apparatus and Procedure

Figure 1 shows a schematic diagram of the experimental apparatus used in the present study. Air supplied from a compressor and water from pump into an air-water mixing section after their flow rates are measured individually by flow meters. The air-water mixture flows through the tube into an air-water separator, where air is released into the atmosphere and water is measured more accurately by weighing if necessary. A smooth tube of 24 mm inner diameter and of 9 m total length is made of transparent acrylic resin to observe the flow pattern.



Tube diameter: 24 mm

P: Pressure gauge	1. Pump
F: Flow meter	2. Compressor
T: Thermometer	3. Air-water mixing section
K: Valve	4. Separator
PR: Pressure regulator	5. Liquid tank
SC: Signal conditioning	
DPT: Differential pressure transducer	
A/D&C: Analog to Digital and Computer	

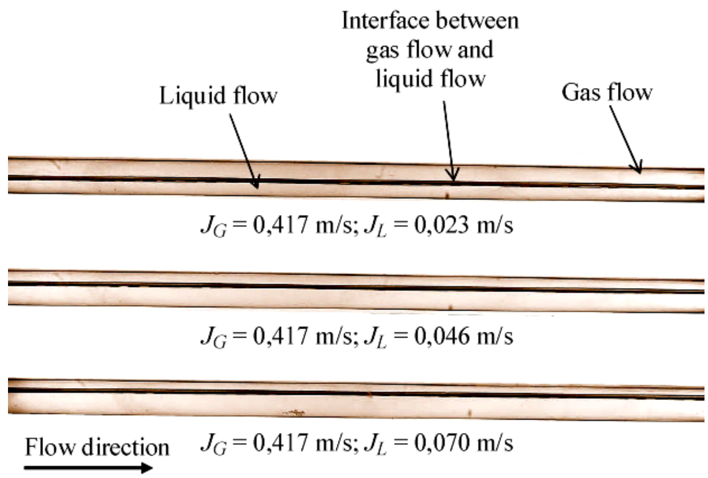
Figure 1. Experimental apparatus.

As shown in the figure, the differential pressure was detected at axially different two locations. It was measured by using a Validyne DP15-32 variable reluctance differential pressure transducer with interchangeable. The transducer has ±0.25% full scale accuracy. Output signals from transducer were sent through amplifier into a computer via A/D converter. Sampling rate was 400 Hz and the measuring time of experimental run was 50 s. The working fluids were air and water. The experiment conditions are as follows: the range of superficial air and water velocities; $J_G = 0.085\text{-}3.204 \text{m/s}$, and those $J_L = 0.016\text{-}1.255 \text{ m/s}$.

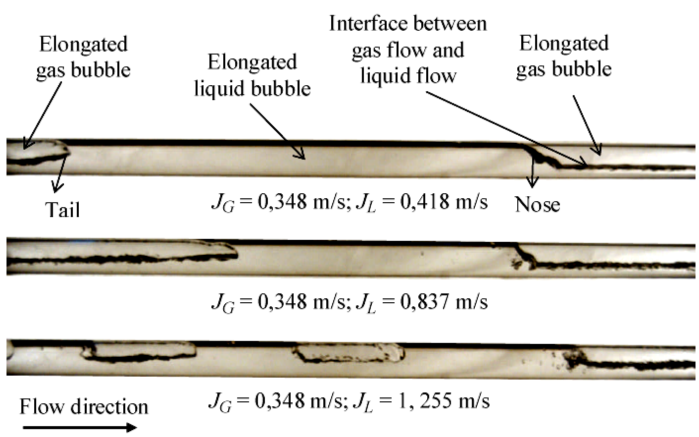
3. Results and Discussions

3.1. Flow patterns

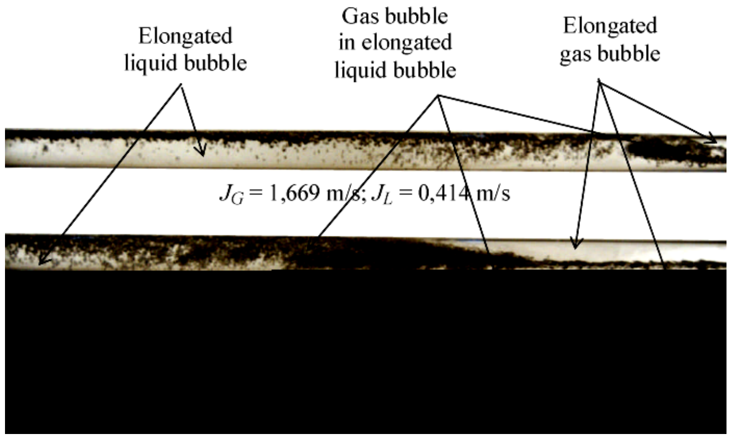
Figure 2 shows the typical results on the flow patterns obtained from the present experiment. The Figures, (a), (b) and (c) correspond to interfacial behavior of the stratified, plug and slug flows, respectively. In the stratified flow, the gas phase travels along the upper half of the tube while the liquid flows along the bottom with no significant interfacial waves. As shown in Figure 2(a), this flow has the simplest configuration of all the horizontal flow patterns. The gravity separation is complete, and the stratified flow regime occurs at relatively low gas and liquid mass flow rates. As shown in the Figure 2(b) the plug flow is characterized by elongated bubbles flowing along the top of the tube in a continuous liquid flow. Next, it is noticed that in the plug flow; elongated bubbles move at the same velocity with the liquid, and the gas-liquid interface below the bubbles is relatively stable, indicating a small difference between the velocities of the phases at the interface. With increased gas velocity, the magnitude of the waves increases. This condition is called *slug flow*. Ultimately, the waves build up and reach the upper wall of the tube to form some liquid packets, also liquid slugs. These liquid slugs are then transported at the higher velocity of the gas (Figure 2(c)). Unlike plug flow, in which the elongated bubbles of gas are transported by the liquid phase, in slug flow the liquid slugs are carried by the faster moving gas flow. The slug flow regime is highly undesirable in practical applications. The faster moving liquid slugs are usually associated with sudden pressure pulses and severe pressure oscillations that can cause damage to downstream equipment.



(a) Stratified flow



(b) Plug Flow



(c) Slug Flow

Figure 2. Typical results of the observed flow patterns.

Finally, the obtained flow pattern data are compared with the horizontal flow regime map of Mandhane et al. [4] as shown in Figure 3. Figure 3 indicates that the obtained flow pattern data are in agreement with those of Mandhane et al. [4].

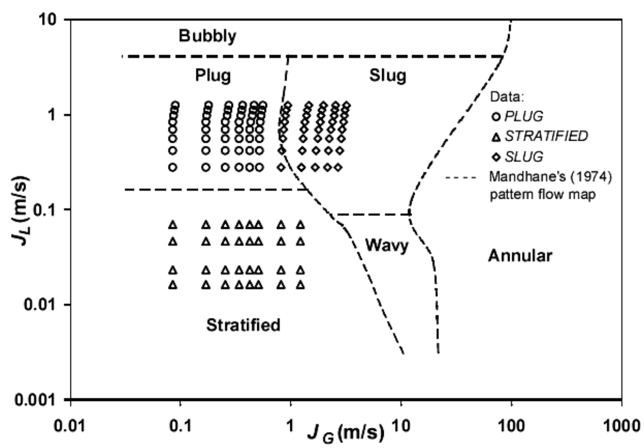
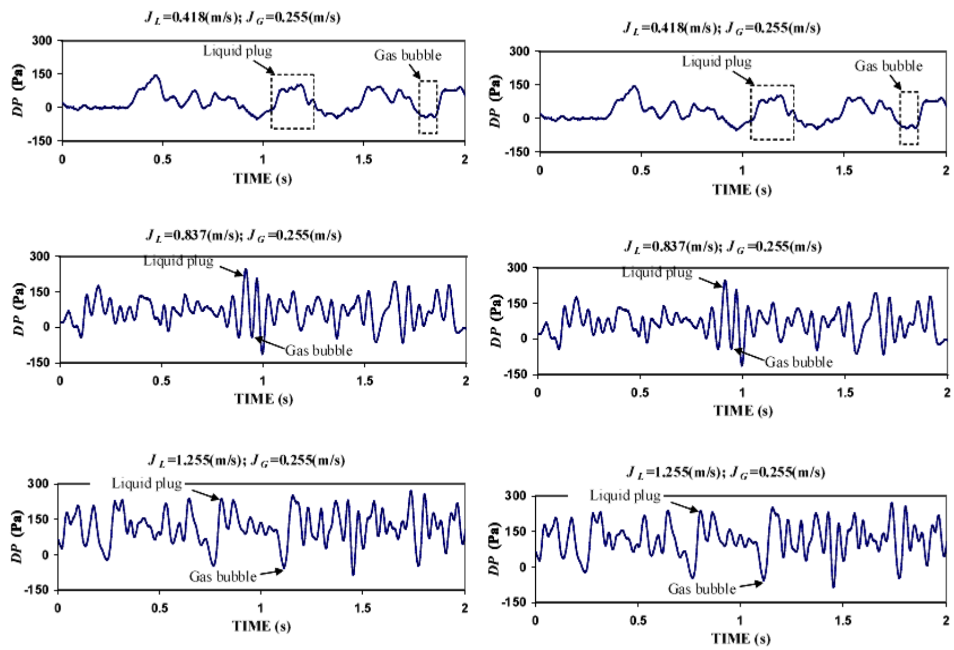


Figure 3. Flow patterns map

Measurements of the differential pressure fluctuations as a function of superficial velocity are presented in Figure 4 with the range of superficial air velocity; $J_G = 0.087\text{-}0.522$ m/s, and those of water: $J_L = 0.279\text{-}1.255$ m/s. They are analyzed by various methods as follows.



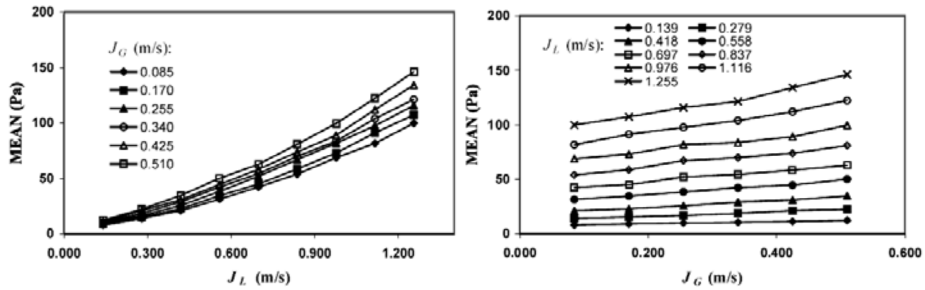
(a) The effect of gas velocity (b) The effect of liquid velocity

Figure 4. Time variations of the differential pressure.

3.2. Statistical analysis

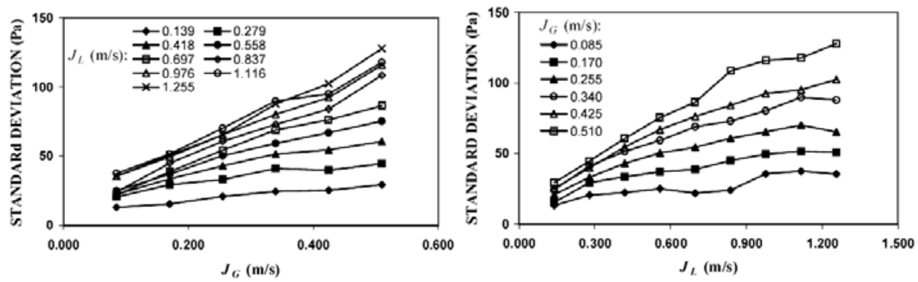
3.2.1. Mean and standard deviation

Figure 5 and Figure 6 display the mean and the standard deviation, respectively. It can be depicted from Figure 5(a) and Figure 6(a) that under the same superficial liquid velocity, the mean and the standard deviation of differential pressure increase linearly with the increase of superficial gas velocity. Meanwhile, smaller superficial liquid velocity corresponds with smaller mean and standard deviation of differential pressure, and the gradient by which the mean and the standard deviation of differential pressure changes with superficial gas velocity also increases with the increase of superficial liquid velocity. Under the same superficial gas velocity, the mean and the standard deviation of differential pressure increase also linearly with the increase of superficial liquid velocity as shown clearly in Figure 5(b) and Figure 6(b).



(a) The effect of the liquid velocity (b) The effect of the gas velocity

Figure 5. Mean of the differential pressure data.

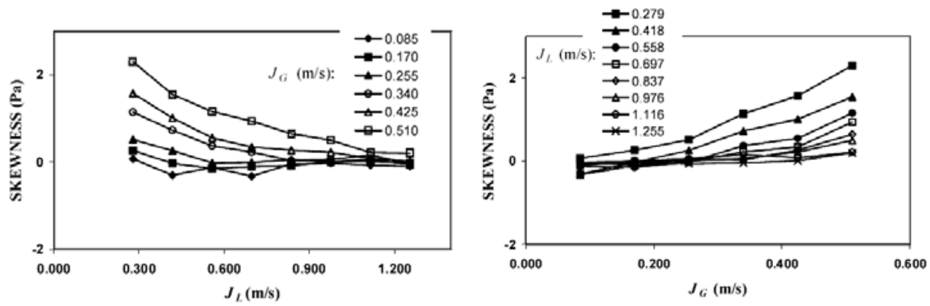


(a) The effect of the liquid velocity (b) The effect of the gas velocity

Figure 6. Standard deviation of the differential pressure data.

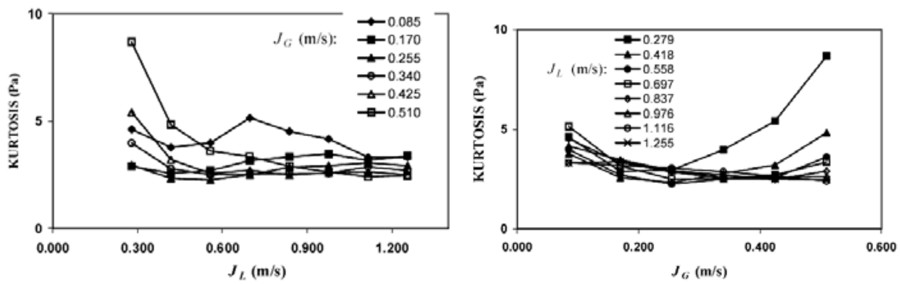
3.2.2. Skewness and Kurtosis

Figure 7(a) and Figure 8(a) show the effect of the superficial liquid velocity in the skewness and kurtosis of pressure difference, respectively. Under the same superficial gas velocity, skewness and kurtosis of pressure difference decreases with the increase of superficial liquid velocity. Next, the effect of the superficial gas velocity on the skewness and kurtosis of difference pressure are shown in Figure 7(b) and Figure 8(b), respectively. As shown in the figure, under the same superficial liquid velocity, the skewness and the kurtosis of pressure difference increases with the increase of superficial gas velocity.



(a) The effect of the liquid velocity (b) The effect of the gas velocity

Figure 7. Skewness of the differential pressure data.

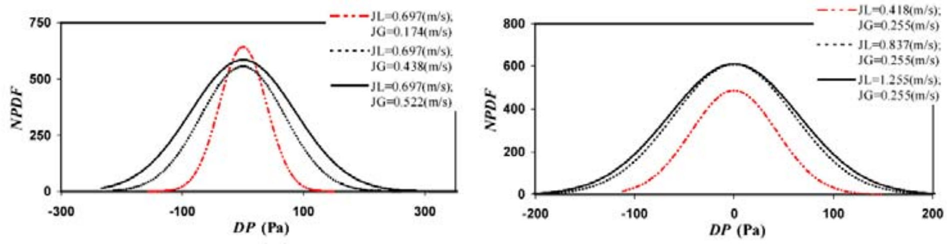


(a) The effect of the liquid velocity (b) The effect of the gas velocity

Figure 8. Kurtosis of the differential pressure data.

3.2.3. Probability density function (PDF)

Figure 9(a) shows the effect of the gas superficial velocity on the probability density function (PDF) of the differential pressure data under a constant liquid superficial velocity. Close observation of the figure reveals that density of PDF is normal density. This typical statistical characteristic can well describe the flow characteristic of plug flow and therefore can provide dependable criteria for recognition of plug flow patterns. Next, the PDF increases with the increase of the gas superficial velocity. Figure 9(b) shows the effect of the water superficial velocity on the PDF data of constant gas superficial velocity. As accepted, the PDF curve increases, with the increase of liquid superficial velocity. It indicated that the passing frequency of the flow; the plug flow morphologies such as elongated bubble and liquid slug increase as the gas and liquid superficial velocities increase.



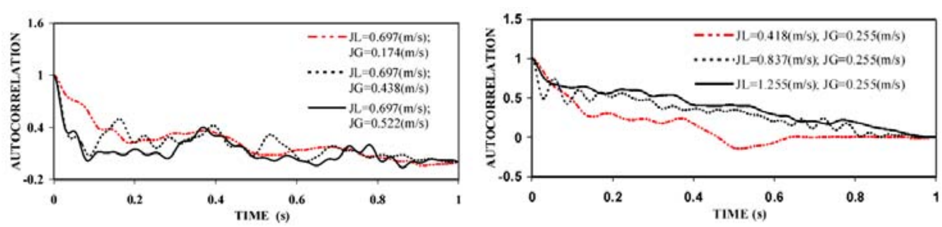
(a) The effect of the gas velocity (b) The effect of the liquid velocity

Figure 9. Probability density function.

3.3. Chaos analysis

3.3.1. Autocorrelation analysis

Autocorrelation function is another signal processing tool used to identify chaotic motions. When a signal is chaotic, information about its past origins is lost. This means that the signal is only correlated with its recent past. The autocorrelation functions of the plug flows are shown in Figure 10. The autocorrelation functions for plug flows have a peak at origin delay time $(t) = 0,$ and drop off rapidly with time, reflecting chaotic behavior. It can be observed from Figure 10 that the plug flows have different periodic oscillations along the time delay axis with the amplitude values of autocorrelation functions around zero.

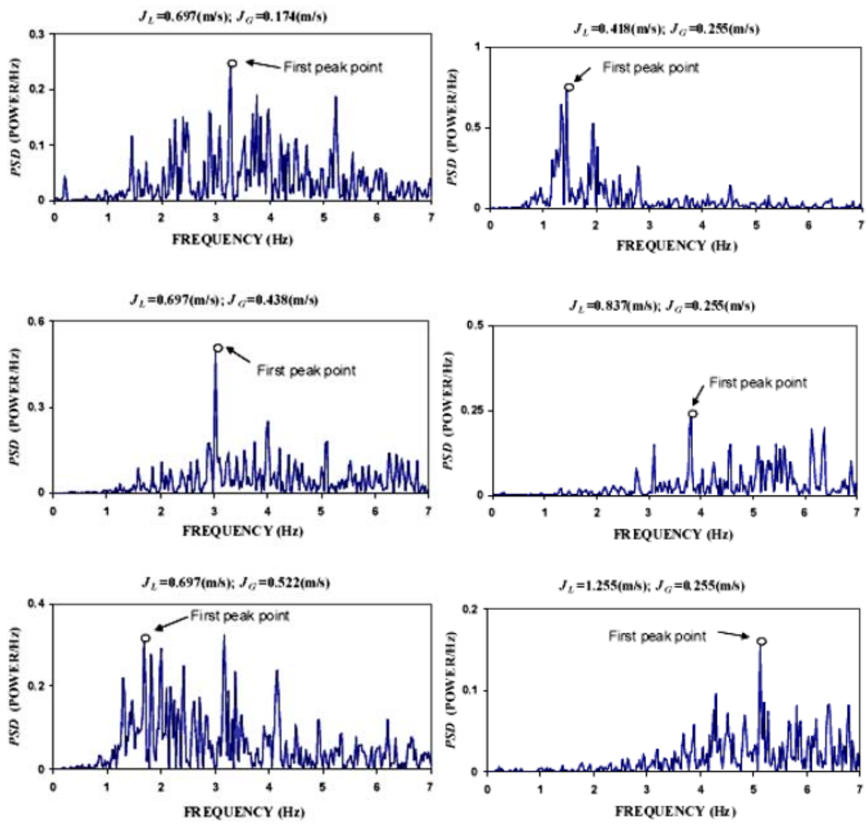


(a) The effect of the gas velocity (b) The effect of the liquid velocity

Figure 10. Autocorrelation of the differential pressure data.

3.3.2 Power spectrum density (PSD) analysis

The PSD is usually employed to extract the periodic feature of a signal to acquire some information on differential pressure fluctuation in frequency domain. In this work, the PSD of the differential pressure fluctuation were computed by the fast Fourier transform (FFT). Figure 11 shows the effect of the gas and liquid velocities on the PSD. Close observation of the figure reveals that the distinct peaks appear between 0 and 7 Hz. These peaks indicate the existence of the elongated bubbles frequencies because the Fourier transform yields the energy density in an individual frequency. As can be seen in the figure, the major peaks move to high frequency with the increased of velocity.



(a) The effect of the gas velocity (b) The effect of the liquid velocity

Figure 11. Power spectral density of differential pressure.

4. Conclusion

Various measurement tools of statistic and chaos theory were applied to analyze two-phase flow plug. These measurement tools include mean, standard deviation, skewness, kurtosis, probability density function, autocorrelation function, and power spectral density function. The mean and standard deviation of differential pressure increases linearly with the increase of superficial gas velocity and the increase of superficial liquid velocity. At the same superficial gas velocity, skewness and kurtosis of pressure difference decreases with the increase of superficial liquid velocity but at the same superficial liquid velocity, skewness and kurtosis of pressure difference increases with the increase of superficial gas velocity. The statistical analysis represents physical phenomenon that mean, standard deviation, skewness and kurtosis change linearly to the superficial velocity. The dispersity of probability density distribution is enhanced with increase of superficial gas velocity and increase of superficial liquid velocity. The application of the power spectral density (PSD) and autocorrelation functions indeed indicates the existence of chaotic behavior in the two-phase differential pressure measurement.

Acknowledgments

This work was supported by DP2M DIKTI (Directorate of Research and Public Service of Directorate General of Higher Education) Ministry of Education and Culture Indonesia through the Competitive Grant Research (*Hibah Bersaing*).

Nomenclature

J_L : liquid superficial velocity (m/s);

J_G : gas superficial velocity (m/s);

DP : differential pressure (kPa);

PDF : probability density function;

PSD : power spectral density.

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