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Transient Analysis of Central Region Void Fraction in a 3x3 Rod Bundle under Bubbly and Cap/Slug Flows

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Abstract**—**This study analyzed the transient signals of central region void fraction of air-water two-phase flow in a 3x3 rod bundle. Experimental tests were carried out utilizing a vertical rod bundle test section along with a set of air-water supply/flow control system, and the transient signals of the central region void fraction were collected through the electrical conductivity sensors as well as visualized via high speed photography. By converting the electric signals, transient void fraction can be obtained through the voltage ratios. With a fixed superficial water velocity (J_f=0.094 m/s), two different superficial air velocities (J_g=0.094 m/s and 0.236 m/s) were tested and presented, which were corresponding to the flow conditions of bubbly flows and cap/slug flows, respectively. The time averaged central region void fraction was obtained as 0.109-0.122 with 0.028 standard deviation for the selected bubbly flow and 0.188-0.221with 0.101 standard deviation for the selected cap/slug flow, respectively. Through Fast Fourier Transform (FFT) analysis, no clear frequency peak was found in bubbly flow, while two dominant frequencies were identified around 1.6 Hz and 2.5 Hz in the present cap/slug flow.

Keywords**—**Central region, rod bundles, transient void fraction, two-phase flow.

I. INTRODUCTION

IN nuclear power plants, water is frequently used as the coolant to remove heat generated during the operation. Meanwhile, water can be boiled and evaporated in the reactor core and forming two-phase flow. As for two-phase flow, several crucial parameters may affect the flow pattern and flow properties, such as the geometries of flow channel, fluid properties, operating temperature and pressure, and so on. In the case of rod bundle geometry, the size of sub-channel, the arrangement of fuel rods, and the casing would influence the formation of bubbles. Previously, several studies have focused on rod bundle geometry with experimental tests and or model development. In 1994, Qazi et al. [1] performed a study of axial void fraction in heated circular rod bundles. Kamei et al. [2] went through experiments with 4x4 rectangular rod bundle under pool condition. In 2012, Chen et al. [3], [4] carried out experimental results and model development of rod bundle. However, most of these studies focused on steady state analysis and utilized global area-averaged properties for analysis without considering the transient and local phenomena. In this study, analysis of transient signals in central region of rod bundle is the focus. Since central region contains most heat in nuclear reactors and that is the region with highest temperature, study of air-water two-phase flow of the central region is crucial. Under chosen parameters, examining the void fraction of two-phase flow in the rod bundle can lead to further understanding of its heat removal capability and operating efficiency as well as safety, which is the first concern during the operation of nuclear power plants.

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II. EXPERIMENTAL FACILITIES

In this study, a 3x3 rod bundle channel is utilized to examine the central region void fraction. Fig. 1 is the schematic diagram of a vertical rod bundle and air-water supply system. A 4-m vertical stainless-steel rectangular rod bundle casing with 5.2 cm side length containing nine circular rods with 1.15 cm diameter and 1.44 cm pitch is applied as the main body of the experimental facilities. There is a 1-m transparent part for visualization and photography on the top and a mixing chamber at the bottom acquiring evenly mixed two-phase flow. Electric conductivity sensors are inserted on the surface of circular rods to ensure no obstructions or interferences in the gas-water channel.

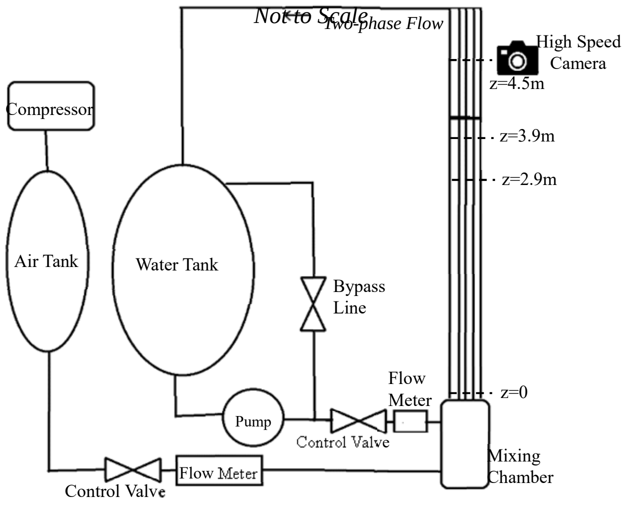


Fig. 1 Schematic of the two-phase rod bundle test facilities

Central region void fraction analysis focuses on the gaps between the central rod and those four rods closest to it, or said the ones surround the central rod as shown in Fig. 2.

Transient void fraction at heights of z=2.9 m and z=3.9 m will be demonstrated in the study to reveal the relations between void fraction and the height. Transient void fraction of two flow patterns, bubbly flow and cap/slug flow will be displayed in this study. With these demands, superficial water velocity J_f=0.094 m/s is set, and the chosen superficial gas velocities are J_g=0.094 m/s and J_g=0.236 m/s for bubbly flow and cap/slug flow, respectively. Table I summarizes all the parameters.

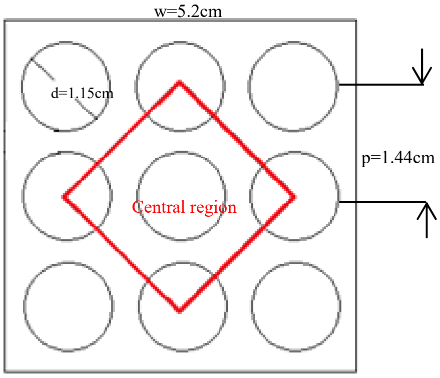


Fig. 2 Cross-sectional view of rod bundle geometry and the central region

TABLE I
PARAMETERS OF THE FLOW CONDITIONS

Flow Pattern	superficial water velocity(m/s)	Superficial gas velocity(m/s)	Height (m)
Bubbly Flow	0.094	0.094	2.9
			3.9
Cap/slug Flow	0.094	0.236	2.9
			3.9

To observe void fraction in a two-phase flow, the measurement of voltage is a more feasible and convenient way in the practice of the experiment. Void fraction can be indicated as shown in (1) by dimensionless voltage which is the ratio of measured voltage to that with the bundle full of water.

$$\alpha = V^* = \frac{measured\ voltage}{voltage\ of\ full\ water} \quad (1)$$

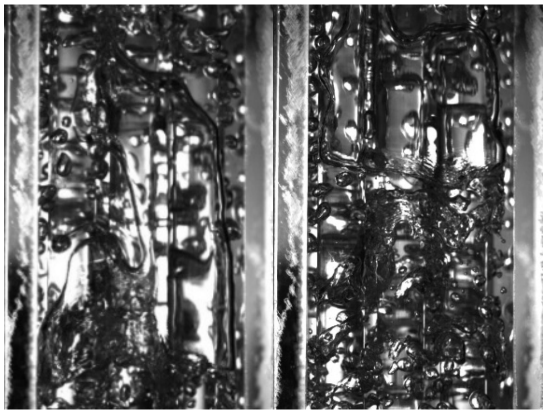
α stands for void fraction and V^*stands for dimensionless voltage. In early study, Chen et al. utilized similar electric conductivity sensors and confirmed that such application led to 20% error or less [5]. Transient signals from the sensors are imported to personal computer through A/D cards.

III. RESULTS AND DISCUSSIONS

Fig. 3 shows the photos of bubbly flow and cap/slug flow taken from the present 3x3 rod bundle under the steady state conditions. In bubbly flow, small bubbles are uniformly distributed within the channel, whereas in cap/slug flow, some larger distorted cap and slug bubbles appeared in central region along with widely spread small bubbles throughout the flow channel.

With J_f=0.094 m/s and J_g=0.094 m/s, the flow pattern is bubbly flow as shown in Fig. 3 (a) and time average central region void fraction is 0.122 at z=2.9 m and 0.109 at z=3.9 m. The standard deviation of central region void fraction in bubbly flow is 0.028. This value is much smaller than that in cap/slug flow due to the low superficial gas velocity. The change of central region void fraction is less intense in bubbly flow because the bubble sizes are smaller and more uniform. Maximum central region void fraction is 0.339 at z=2.9 m and 0.311 at z=3.9 m. The maximum values shown and Fig. 4 both indicate that void fraction at z=2.9 m is higher than that at z=3.9 m.

(a) Bubbly flow



(b) Cap/slug flow

Fig. 3 Photos of two-phase flow patterns with (a) bubbly flow and (b) cap/slug flow in the present 3x3 rod bundle

The other case is operated under J_f=0.094 m/s and J_g=0.236 m/s. Cap/slug flow is then performed in this case as shown in Fig. 3 (b) with time average central region void fraction 0.221 at z=2.9 m and 0.188 at z=3.9 m, which are almost twice as those in bubbly flow. Maximum void fraction is 0.809 at z=2.9 m and 0.775 at z=3.9 m. Standard deviation is 0.101 in cap/slug flow. First of all, these two maximum numbers are significantly larger than those in bubbly flow. Secondary, the impulses in Fig. 5 are much more intense and severe. Last but not least, those big bubbles also make peaks in Fig. 5 and they last longer in time. Time length of bubbles at z=2.9 m is roughly longer than that at z=3.9 m.

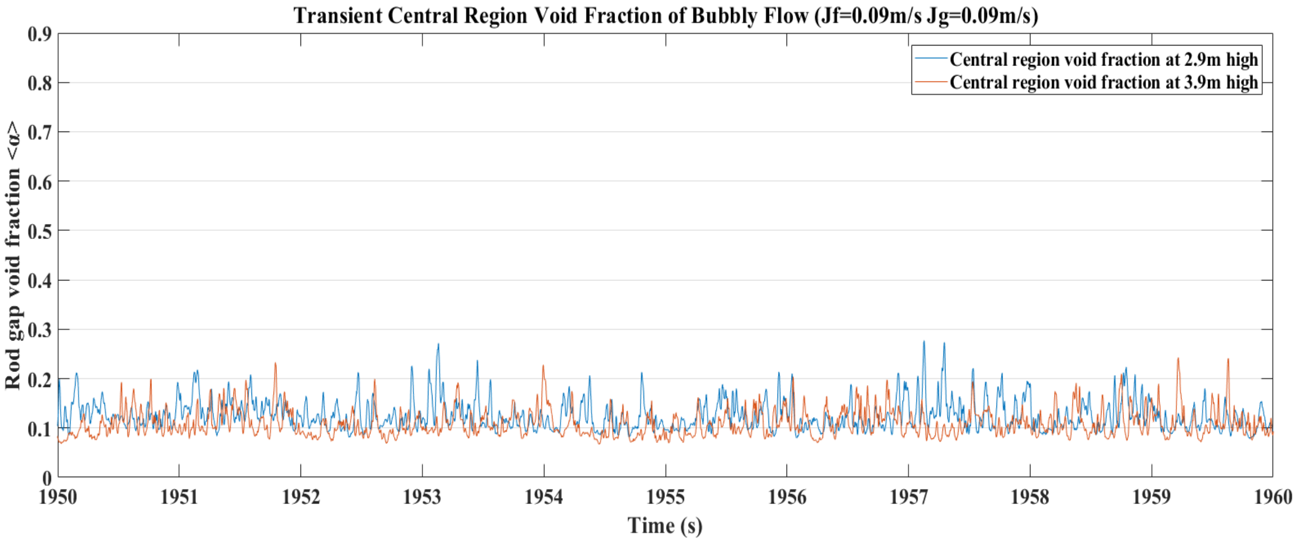


Fig. 4 Transient void fraction signals of bubbly flow

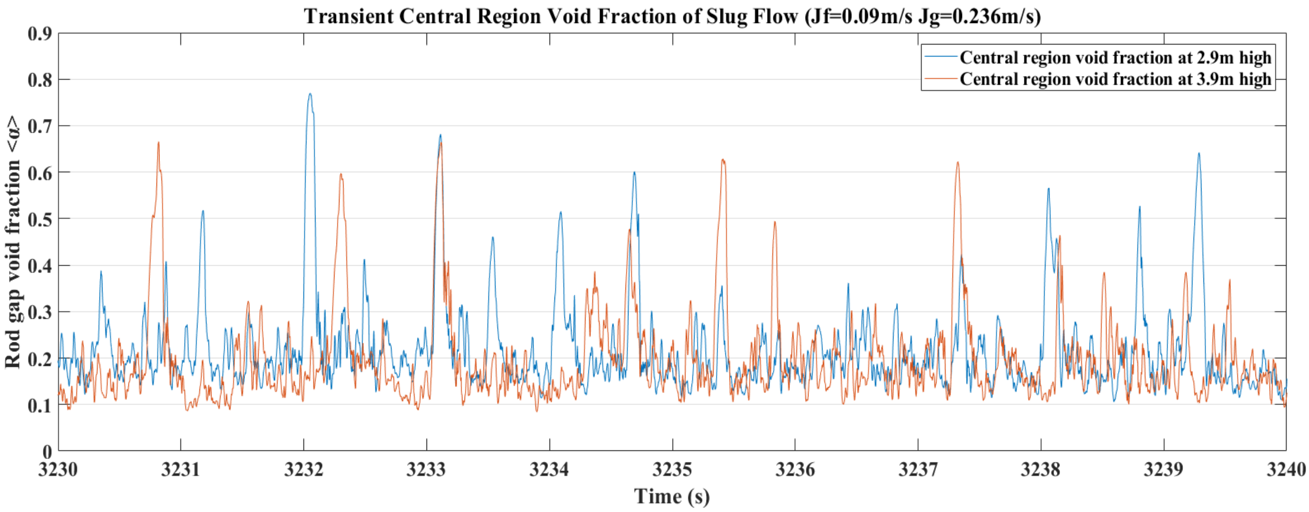


Fig. 5 Transient void fraction signals of cap/slug flow

Those two cases chosen and analyzed in this study are shown in Fig. 6 with important statistic parameters. It is obvious that in both bubbly flow and cap/slug flow, z=2.9 m sensors measure larger time average central region void fraction, as well as maximum and minimum values, than that at z=3.9 m. An explanation of this phenomenon is that bubbles might break throughout the flow advancing by chance, but no new bubble will be generated in the bundle, since the system is not heated, leading to a decrease on the number as well as volume of air bubbles. However, standard deviation remains the same despite the change of height, yet its change is corresponding to the change of superficial gas velocity, also defined as different flow patterns. It is intuitive that higher superficial gas velocity with set superficial water velocity, standard deviation increases due to the formation of larger bubbles. In cap/slug flow, large bubbles causing 0.8 maximum void fraction and small bubbles with 0.1 minimum void fraction exist at the same time and that huge variety of bubble leads to a much larger standard deviation in statistic point of view.

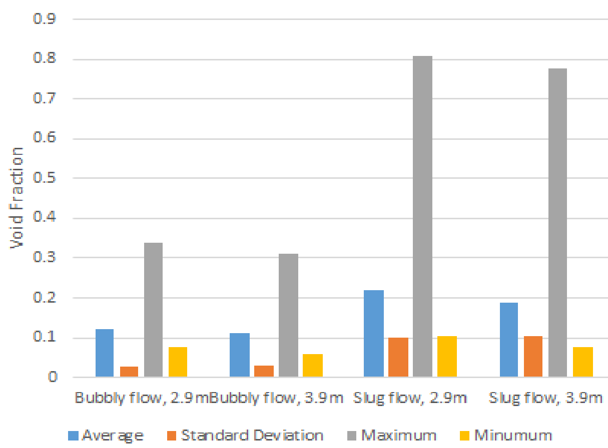


Fig. 6 Statistic parameters of void fraction signals

By performing FFT analysis to transient void signals, the results are shown in Figs. 7 and 8. In bubbly flow, there are several peaks in frequency, but none of them could be noted as dominant frequency at both heights. On the contrast, 1.6 Hz and 2.5 H are dominant frequencies in cap/slug flow at both heights. That is, dominant frequencies only exist in high superficial gas velocity due to the more significant size differences in bubbles. Larger bubbles appeared in cap/slug flow causes peaks in signals as shown in Fig. 5 with similar frequencies to the results done by FFT. Furthermore, heights barely influence the result of frequency analysis since the effect of height on bubble size differences is trivial.

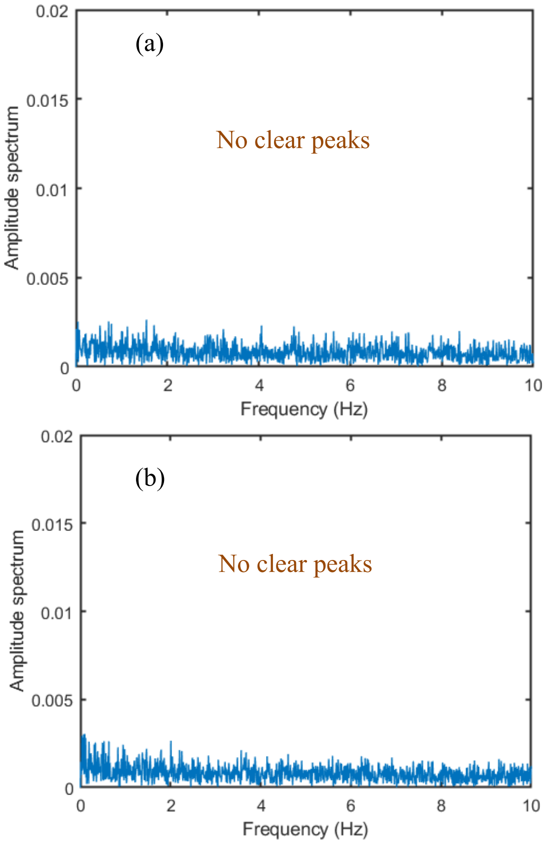
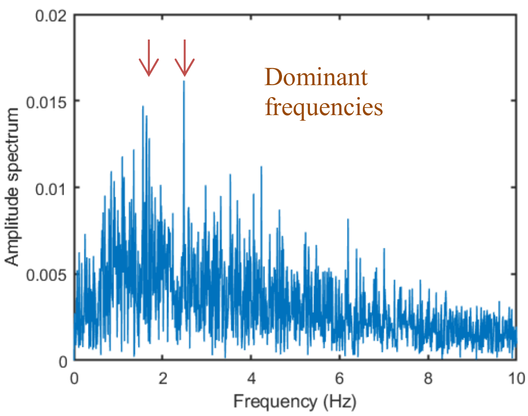
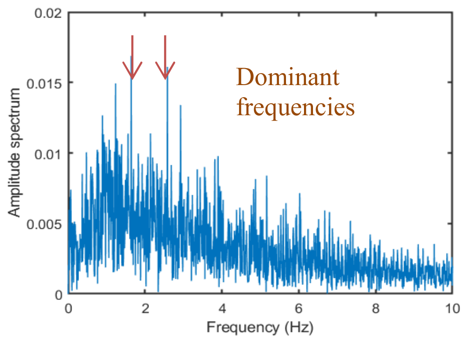


Fig. 7 FFT of transient void signals of bubbly flow at: (a) z=2.9 m and (b) z=3.9 m



(a)



(b)

Fig. 8 FFT of transient void signals of cap/slug flow at: (a) z=2.9 m and (b) z=3.9 m

IV. Conclusion

In this study, a set of air-water two-phase flow tests have been carried out using a 3x3 rod bundle test section with a casing width of 5.2 cm and a rod diameter of 1.15 cm. The tests were operated at a constant J_f =0.094 m/s along with J_g=0.094-0.236 m/s conditions, which were corresponding to bubbly and cap/slug flows. The transient central region void fraction during the tests was recorded and analyzed. It appears that both time average and maximum central region void fraction is much smaller in bubbly flow. On the other hand, there are not only higher void fraction but also more intense and long-lasting signal impulses in cap/slug flow because of the higher speed and larger size of the bubbles. However, in both cases of bubbly and cap/slug flows, void fraction decreases through the process flowing upward. Besides, the rate of decrease in void fraction in cap/slug flow is larger. In frequency analysis, at both heights of z=2.9 m and 3.9 m, there is no clear peak found in bubbly flow, whereas 1.6 Hz and 2.5 Hz are observed as the dominant frequencies in cap/slug flow.

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