Experimental Study of Air–water Two-phase Flow in a 3×3 Rod Bundle for PDF Analysis

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Abstract - The objective of this study is to investigate the void fraction distributions by examining the Probability Distribution Function (PDF) of local void fraction in a 3x3 rod bundle geometry. A series of experiment has been carried out with air-water two-phase flow. The experimental tests were performed under the flow conditions of $J_g = 0.076\text{--}0.24$ m/s and $J_f = 0.14, 0.19$ and 0.24 m/s. Two sets of conductivity probe arrangements were used to measure the local void fractions in the regions of “rod-gap” and “sub-channel”. It was observed that while the superficial gas velocity increases, the peak regions of probability distribution function may become broadened; whereas the peak values of PDF may be shifted to the left as superficial liquid velocity increases. In addition, the PDF peak values of both regions tended to stay closer and become more overlapped with increasing superficial gas and liquid velocities.

Keywords: conductivity probes, rod bundles, two-phase flow, void fraction.

1. Introduction

Two-phase flow systems are one of the most widely used systems in various engineering systems and have been extensively used for the nuclear science and engineering. The two-phase mixture in the rod bundle can be affected by many parameters, including superficial gas velocity, superficial liquid velocity, void fraction, slip ratio, and physical characteristics of the fluid. Void fraction of two-phase flow can play an important role in the safety analysis of nuclear power plants. It is especially essential for boiling water nuclear reactors since two-phase flow is involved in the standard operational conditions of BWR. Several methods currently exist for the measurement of two-phase flow, such as electrical conductivity probe, impedance meter, high speed camera and so on. Chen et al. [1] utilized the impedance void meters to measure area-averaged void fraction at various axial locations in an 8×8 rod bundle. Local conductivity probes have also been used to measure the local void fraction [2]. Kok et al. [3] developed a subchannel void-fraction measurement system based upon the gamma-transmission technique and applied to a scaled model of a BWR fuel assembly. Electrical conductivity probes have been used in the past to investigate void fraction, gas velocity and other information of the two-phase mixture and they were also utilized in this study to measure local void fraction. Zhou et al. [4] performed steam-water experiments in 3×3 heated rod bundles at atmospheric condition and they investigated four flow regimes, including bubble, bubble-churn, churn and annular flow. However, because of the surface instability, slug flow could not be observed.

2. Experimental Facility

2.1. Test loop

A schematic of the experimental facilities used in this experiment is shown in Fig. 1. The water from the water tank passing through the flow meter and the flow control valves is pumped into the mixer. The air is compressed by the compressor and stored in the air tank. After the air passes through the flow meter and the flow control valves, it mixes with the water in the mixer. The two-phase mixture flows into the rod bundle test section after fully mixing. The rod bundle test section is divided into three regions, including the entrance region, the measurement region, and the visualization region. There are three pressure sensors at different height and several electric conductivity sensors which are embedded in the rods and the right and left sides of the casing. The test-section in cross-section view is shown in Fig. 2. The casing of the rod bundle test section is made of aluminium. The casing has a square cross-section with sides 52 mm in length. There are a total of 9 rods inside the rectangular casing. The rod diameter is 11.5 mm and the rod pitch is 15.4 mm. It is different from the entrance region and the measurement region, the rectangular duct and the rods of the visualization region are made of transparent acrylic. The image in the test section will be captured by utilizing the high speed camera setting up at the visualization region.

Fig. 1: Schematic of 3×3 rod bundle test facilities [5].

Fig. 2: Cross-sectional arrangements of conductivity probes in the rod bundle [5] (sub-channels: 5-1, 5-3, 5-7, 5-9; rod-gaps: 5-2, 5-4, 5-6, 5-8).

2.2. Electrical Conductivity Probes

The study used electrical conductivity probes in order to determine the void fraction of the two-phase mixture by the measured voltage during the tests. One advantage of the electrical conductivity probes used in this study is that it avoids the problem of affecting the flow field of two-phase flow because the electrical conductivity probes are ring-shaped and mounted on the rods. Therefore, the average void fraction in a single sub channel can be measured, and the flow field would not be interfered. The dimensionless voltage can be used to determine the void fraction of two-phase flow mixture due to the difference between the dielectric constants of air and water is large. The voltage of two-phase flow can be turned to dimensionless voltage through dividing by the voltage of full water. The relation of void fraction and dimensionless voltage is shown below:

$$\alpha = V^* = \frac{V_{two-phase}}{V_w} \quad (1)$$

Where α is the void fraction, V^* is dimensionless voltage, $V_{two-phase}$ is the voltage of two-phase flow, and V_w is the voltage of full water.

3. Results and Discussion

The position of the chosen electrode sensors was at 3.4m height. The regions which were chosen to be detected are sub-channels and rod-gaps in this study. The conductivity probes measured the void fraction signals of four individual sub-channels and four individual rod-gaps under various test conditions. This study analyzed the void fraction of the two-phase flow by comparing the probability distribution functions of the void fraction in the regions of “sub-channels” and “rod-gaps”. The probability distribution function (PDF) is a function of the signal amplitude and is a measurement of the probability that the signal will have a certain range of values [6]. This study used the void fraction PDF of different regions, and compared them to illustrate the differences between the ratio of void fraction in different flow channels. Fig. 3 shows the probability distribution function of void fraction in sub-channels and rod-gaps under different flow conditions. The legends of 5-1, 5-3, 5-7, 5-9 represent the sub-channel regions, and the legends of 5-2, 5-4, 5-6, 5-8 express the rod-gap regions. All the peaks of PDF in different regions were concentrated under low superficial gas velocity. As superficial gas velocity increased, the probability of high void fraction increased and the peaks of the probability distribution function broadened. At the same superficial gas velocity, the bubble size became smaller with J_f increasing, and the peaks shifted to the left. The results of this study showed that the bubble distribution could be more uniform with J_g increasing because the peak of PDF in the sub-channels and the rod-gaps are gradually getting closer. The peaks also became more overlapped as J_f increased by comparing the probability density functions under constant J_g . Fig. 4 shows the average void fraction corresponding to the highest point of PDF under various test conditions. The bubble distribution could be more uniform, according to the lines of the sub-channels and the rod-gaps in Fig. 4 were gradually getting closer with increasing J_g .

(a) PDF at flow conditions of $J_g=0.076\text{-}0.24\text{m/s}$ and $J_f=0.14\text{m/s}$.

(b) PDF at flow conditions of $J_g=0.076\text{-}0.24\text{m/s}$ and $J_f=0.19\text{m/s}$.

(c) PDF at flow conditions of $J_g=0.076\text{-}0.24\text{m/s}$ and $J_f=0.24\text{m/s}$.

Fig. 3: The PDF of void fraction in the regions of sub-channels (5-1, 5-3, 5-7, 5-9) and rod-gaps (5-2, 5-4, 5-6, 5-8).

Fig. 4: the average void fraction corresponding to the highest point of PDF under various test conditions.

4. Conclusion

In this study, experimental tests of air-water two-phase flow in a 3x3 rod bundle test section have been carried out. The test flow conditions covered the ranges of $J_f \approx 0.14, 0.19$ and 0.24 m/s, and $J_g \approx 0.076$ - 0.24 m/s. The local void fraction signals in the regions of sub-channels and rod-gaps were measured by the conductivity probes, and the PDF of local void fraction was analyzed to understand the distribution of the local void fraction in the rod bundle. The results of this study indicated that the peaks of the probability distribution function may be broadened as J_g increased, and the peaks of PDF tended to shift to the left with increasing J_f . Moreover, the bubble distribution could be more uniform with increasing J_g and J_f , and the differences between the peak values were less than 0.06. This study has successfully demonstrated the variations of local void fraction in the rod bundle geometry, and further experiments with wider test conditions are suggested as future work to explore more characteristics of two-phase flow in a rod bundle.

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