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Experimental Investigation of Local Bubble Parameters for Low-Pressure Subcooled Boiling Flow in Rod Bundle Channel

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1. Introduction

Subcooled boiling in rod bundle geometry is one of the important phenomena observed in small break loss of coolant accident (SBLOCA) for PWR and loss of cooling of spent fuel pools (SFP). In this situation, local two-phase parameters such as a void fraction, bubble velocity, and interfacial area concentration (IAC) have a significant effect on the interfacial heat and mass transfer between the two phases. To predict accurately this phenomenon in bundle geometry, it is necessary to develop of thermal-hydraulic model and correlation based on experimental data. However, few experimental data for the local two-phase flow parameters are available in the rod bundle.

In this study, the experiment was conducted at the subcooled boiling flow of water using a 4 × 4 rod bundle heaters and local bubble parameters are obtained by using a four-sensor optical fiber probe (4S-OFP) under low-pressure condition.

2. Experimental Setup

In this section experimental facility, measurement method, and experimental conditions are described. The experiment was carried out under subcooled boiling flow inside the 4 × 4 rod bundle channel, and the local bubble distribution data of the channel cross-section were acquired by applying a 4S-OFP

2.1 Experimental apparatus

The experiments were conducted using a closed loop system. The loop comprised a test section, circulating pump, separator, condenser, heat exchanger, water tank, pressurizer, and preheater. The working fluid, deionized water, was provided to the test facility.

Fig. 1 shows the test section. It is a square channel with a width, depth, and height of 85, 85, and 610 mm, respectively. Each rod is 16mm in diameter and 590mm in heated length. A pitch to diameter is 1.3 in bundle arrangement. Distributions of the local void fraction, interfacial velocity, interfacial area concentration (IAC), and Sauter mean diameter were measured with the 4S-OFP. A 4S-OFP consisting of one front sensor and three rear sensors was applied to measure the local two-phase flow parameters. The local void fraction, IAC, bubble velocity, and bubble diameter were measured by analyzing the signal change that occurred when the bubble passed through the OFP sensor in the two-phase flow. For details on how to measure using 4S-OFP, see Moon et al. [1] and Kim et al. [2]

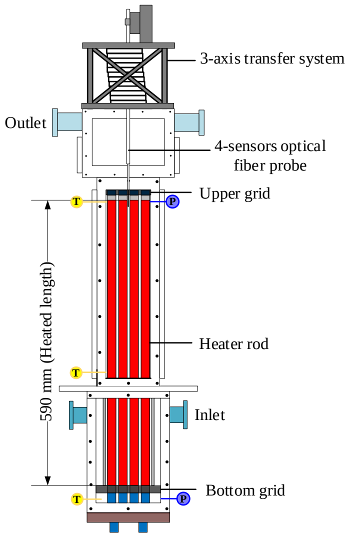

Fig. 1 Test section

2.2 Experimental conditions

As summarized in Table 1, three experimental conditions were prepared as a test matrix to investigate the distribution of local two-phase flow parameters according to mass flux. In all experiments, the inlet pressure was maintained at 2 bar. The 4S-OFP for the measurement of local bubble parameters was placed at Z_h/D_h =41.4 at the beginning of the bundle heater. The probe was traversed to cover 1/4 of the central sub-channel using a three-axis traverse system installed on top of the test section as shown in Fig. 1. The total number of measuring points is 37.

Table 1 Experimental conditions

Mass flux (kg/m^{2}s)	**Heat flux** (kW/m^2)	**Inlet subcooling temperature** (°C)
350	190	22.5
350	210	22.5
350	230	22.5

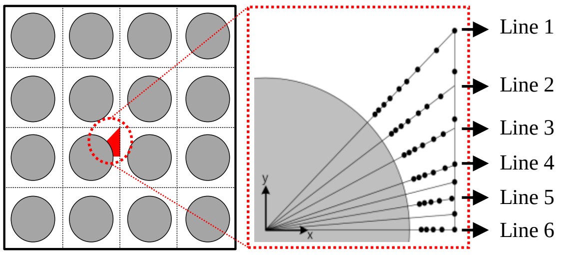

Fig. 2 Measurement points in the central sub-channel

3. Results and Discussion

Fig. 3 shows the distribution of the local bubble parameters according to the mass flux in the central sub-channel. The void fraction of the entire channel increased as the mass flux decreased, as shown in Fig. 3. The void fraction is higher in the narrowest gap (Line 6) than in the center of the sub-channel (Line 1). It is also reported that the same distribution was observed in rod bundle channels under air-water flow([3] and [4]). This phenomenon happens because the combined effects of a relatively low liquid velocity in the narrowest gap and the lift force acting toward the wall on the small bubble enhances the void fraction at the narrowest gap between the rods. In the low mass flux condition (G=305 kg/m^{2}s, $\Delta T_{sub,in}$=22.5 ℃, q''=220 kW/m^2), the void fraction decreases as the heater rod is approached, but in the high mass flux condition (G=390 kg/m^{2}s, $\Delta T_{sub,in}$=22.5 ℃, q''=220 kW/m^2), a maximum value is achieved close to the heater rod because the number of bubbles generated on the surface of the heater rod increases with the increase of the water temperature. In addition, at high mass flux conditions, the void fraction exhibits a wall peak profile at all lines as shown in Fig. 3. However, when the distance between the heater rods decreases (i.e. the number of lines increases) under the low mass flux condition, the wall peak profile changes to the core peak profile. At low mass flux condition, the void fraction near the wall decreased in the narrow gap (Line 6). A high void fraction appeared in the narrow gaps between the adjacent heater rods in each sub-channel and between the wall and heater rod, primarily owing to the low water velocity resulting from the wall shear stress of the channel and heaters [5].

IAC shows a similar tendency to the void fraction because it is proportional to the void fraction in the bubbly flow condition. IAC has been great at low mass flux condition as smaller air bubbles appear on the heater wall than the center of the subchannel.

The bubble velocity and bubble diameter also decreased with the decreased void fraction and IAC according to increasing mass flux. Under the experimental condition of G=305 kg/m^{2}s, which was the lowest mass flux examined in the present experiments, the bubble diameter had a large value around the heater rods but decreased as it approached the center of the sub-channel. While, the bubble diameter was larger at the center of the sub-channel than around the heater rod under the lowest mass flux condition (G=390 kg/m^{2}s) because as the mass flux decreased, the thickness of the bubble boundary layer increased due to the increase in the bubbles generated from the heater rod, resulting in the increased coalescence of bubbles. Furthermore, the low bubble condensation also contributes to this phenomenon owing to the increase in the bulk temperature of the water. This tendency was also observed in the experimental results obtained by Yun et al. [6].

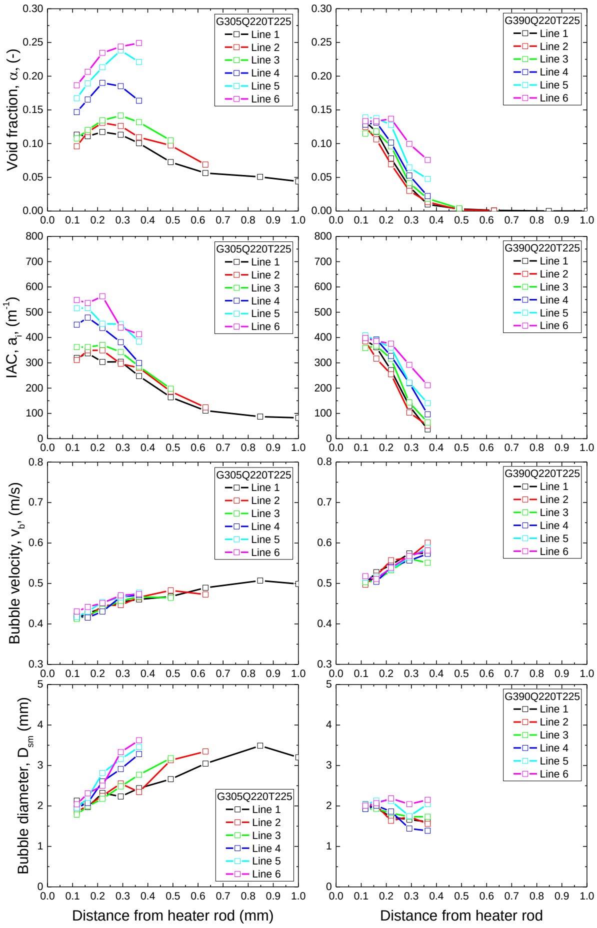

Fig. 3 Distribution of local bubble parameter according to the mass flux in the central sub-channel

4. Conclusions

In this study, a subcooled boiling flow experiment was conducted in a 4 × 4 rod bundle geometry under low-pressure conditions. The experiment was performed under three thermal-hydraulic conditions, with the distribution of the local two-phase flow parameters measured within an octant triangular region of the central sub-channel using a 4S-OFP.

The experimental results showed that the local void fraction increased as the gap between the adjacent heater rods decreased. When the mass flux was high, the void fraction had a wall peak profile at all measurement lines. However, when the mass flux was low, the wall peak profile appeared only in the wide gap region and changed to a core peak profile in the narrow gap region. The bubble diameter reached its maximum near the heater rod when the mass flux was high. This maximum was located towards the center of the sub-channel as the mass flux decreased.

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