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Experimental Study on Local Bubble Parameters in a Low Pressure Subcooled Boiling

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1. Introduction

Subcooled boiling is one of the crucial phenomena in a design, operation and safety analysis of a nuclear power plant. Recently, the safety analysis for the APR1400 (Korean advanced power reactor) showed that subcooled boiling phenomena in the reactor downcomer results in a reduction of the reflood flow rate for the core cooling in a postulated large break loss of coolant accident (LBLOCA) [1]. However, it was found that most of the existing best estimate safety analysis codes have some weakness in the prediction of subcooled boiling phenomena, especially in a low pressure condition.

For a better prediction of these subcooled boiling phenomena, development of advanced analysis tools or improvement of related models for the existing prediction tools is required. However, the available data is still lacking for them in previous studies. In this study, subcooled boiling test was performed in the SUBO (Subcooled boiling) test facility to extend the data base for a higher mass flux and heat flux condition. From the experiments, the characteristics of the local bubble parameters in a subcooled boiling two-phase flow are investigated.

2. Test Facility and Measurements

2.1 Test Facility

In order to investigate the subcooled boiling phenomena and measure the local bubble parameters, SUBO (Subcooled Boiling) facility was constructed [2]. The test section of the facility is a vertically arranged annulus with an in-direct heater rod at the channel center. The inner diameter of the test section is 35.5mm and the outer diameter of the heater rod is 10.02mm. The heater rod consists of three parts. The first part is an unheated section with 222mm in length for regulating the water condition at the inlet, the second part is a heated section with 3098mm in length for a simulation of the boiling, and the third part is an unheated section with 800mm in length for the bubble condensation at the top region.

2.2 Measurement of Local Bubble Parameters

In order to measure a complex behavior in a two-phase flow condition, a double sensor conductivity probe has been widely used. It can measure the local time-averaged void fraction, bubble velocity, and interfacial area concentration by transforming the electric signal from two tips. However, the use of a conductivity probe is limited to an electrically conducting fluid and it provides a slow change of a signal due to a lower sensitivity on the conductance in the fluid. To resolve this problem, an optical fiber probe is utilized in this study. A tip of the optical probe can distinguish the phase at a local position by the characteristics of the light penetration, so that the electrical conductance of a working fluid is not relevant to the measurement. Also, it is insensitive to the temperature or pressure condition of fluid and it can provide a stiff change of a signal depending on a phase. The senor size of optical fiber probe can be minimized, so it is beneficial with respect to the problem of a flow disturbance by the sensor.

For the measurement of the local bubble parameters, double optical fiber sensors were applied at six elevations along the test section. Among them five (L/D_h=17.6, 42.5, 66.4, 91.7, 116.2) were installed in the heated region and one (L/D_h=141.2) was installed in the unheated condensation region. Those instruments can also be traversed through 12 positions in a radial direction at each level, so that a multi-dimensional structure of the two-phase flow can be understood.

3. Experimental Results

3.1 Test Matrix

The test condition of SUBO experiments is summarized in Table I. SUBO has a capacity for simulating experimental conditions for a higher heat flux and mass flux in a longer vertical channel. Outlet pressure was maintained around 155kPa in all cases. When compared with the Base case, Q1 and Q2 cases are tested to investigate the effect of a heat flux. Moreover, in order to observe the subcooled boiling phenomena according to various conditions, V1 and V2 cases have a higher mass flux than the base case and T1 case has a higher inlet subcooling condition.

Table I: Test matrix

Case	Heat flux (kW/m^2)	Mass flux (kg/m^2s)	Inlet subcooling (K)
Base	470.6	1132.6	19.1
Q1	363.7	1119.6	19.0
Q2	563.0	1126.9	18.3
V1	465.7	2126.5	19.6

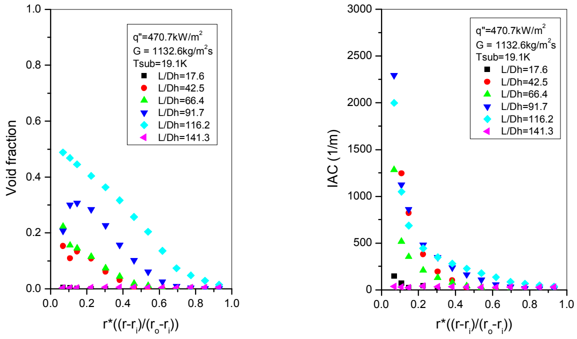
V2	567.9	2128.8	19.5
T1	465.5	1103.9	29.6

3.2 Results

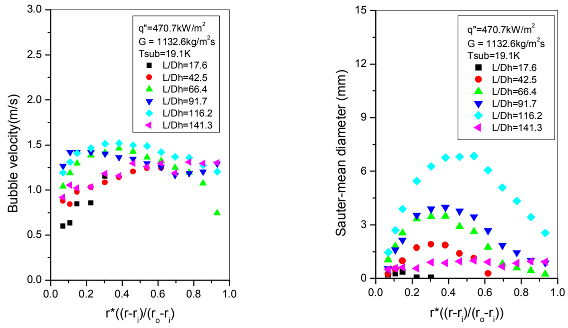
Figure 1 shows the radial and axial distribution of the void fraction, interfacial area concentration, bubble velocity, and Sauter-mean diameter in the Base case. As shown in the figure, the radial distribution of the void fraction indicated the existence of bubbly boundary layer near the heated surface, which is one of the representative characteristics in the subcooled boiling phenomena as reported by Lee (2002) [3]. It was shown that the bubbly boundary layer was increasing as the fluid flowed toward the downstream within the heated section. Q1 case with a lower heat flux indicated a lower void fraction than the Base case and the bubbly boundary layer could not cover the whole flow channel even at the position of L/D_h=116.2. Q2 case with a higher heat flux indicated a larger void generation and a thicker bubbly boundary layer than the Base case or Q1 case. On the other hand, results of the V1 and V2 cases presented the effect of an increased mass flux when compared with the Base and Q2 case, respectively. Larger mass flow in the channel reduced an enthalpy rise of the fluid while flowing through the heated section, so that the thickness of the bubbly boundary layer was reduced by a decreased void generation. T1 case had a larger inlet subcooling and it decreased the amount of vapor generation.

In the case of the distribution of the interfacial area concentration, as revealed in Fig. 1(b), the amount of interfacial area concentration was closely related to the void fraction and the dependency on the heat flux or mass flux condition could be explained with the same reason discussed in the above section. However, it is observed that a sharp increase of the interfacial area existed near the heated wall and the maximum value of the interfacial area concentration adjacent to the wall was not in an order of the heated length, L/D_h. That means the coalescences between departed bubbles from the heated surface occurred more vigorously and it affected a decrease of the interfacial area concentration at a higher elevation.

As shown in Fig. 1(c) and 1(d), the peak values of the bubble velocity and the Sauter-mean diameter appeared within the central region of the flow channel rather than near the wall. It was caused by the buoyancy effect, that is, the bubble with a larger diameter due to the coalescence interactions could obtain a larger buoyancy force and be accelerated faster than the small bubbles near the wall. With flowing toward the downstream, the bubble velocity is not significantly increased due to the momentum balance between the interfacial frication and the buoyancy force. The high heat flux generated a larger amount of steam in the test section and it increased the bubble velocity. In the V1 and V2 cases with the larger mass flux, although the void generation was lower than the Base or Q2 case due to the higher subcooling of the fluid, the bubble velocity was increased by the interaction with the liquid phase.



(a) Void fraction (b) IAC



(c) Bubble velocity (d) Sauter-mean diameter

Fig. 1. Local bubble parameter distribution of Base case

4. Conclusions

This study focused on an investigation of the subcooled boiling two-phase flow with measuring local bubble parameters. Considering the multi-dimensional behavior in a two-phase flow, axial and radial measurements of the local void fraction, interfacial area concentration, and bubble velocity were conducted by an installment of the optical fiber probe. Experimental results showed the characteristics and the propagation of the bubbly boundary layer and interfacial area well, depending on the heat flux or mass flux conditions. The present data will be suitable for a benchmark, verification and model development for the CFD style codes or existing safety analysis codes.

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