Measurement of Multi-Dimensional Distribution of Local Bubble Parameters in a Vertical Annulus under Subcooled Boiling Conditions

Yeon-Gun Lee [a*], Ji-Woong Yoo [a], Sin Kim[b]
[a]*Department of Nuclear and Energy Engineering, Jeju National University, 102 Jejudaehakno, Jeju-si, Jeju, KOREA*
[b]*School of Energy Systems Engineering, Chung-Ang University, 84 Heukseok-ro, Dongjak-gu, Seoul, KOREA*
[*]*Corresponding author: yeongun2@jejunu.ac.kr*

1. Introduction

The behavior of generated bubbles near the heated surface by subcooled boiling influences the heat transfer characteristics and the pressure drop in the system. While the nuclear power plants (NPPs) operates at high pressure of around 15.5 MPa, the subcooled boiling may take place at low pressure near the atmospheric pressure under accidental conditions. For example, the low-pressure subcooled boiling can occur in the heat transfer process of the passive heat exchanger submerged in a large pool, and the severe accident mitigation features such as the core catcher and so on.

At near-atmospheric pressure, the vapor bubbles exhibit complicated behaviors since they have various size including large ones over a few millimeters, generally not formed at high pressure conditions. Then the magnitude and even the direction, in some cases, of non-drag forces are changed compared to those at high pressure.

In this study, an experimental investigation was performed to measure the local bubble parameters in steam-water subcooled boiling flow in a vertical channel at low heat and mass flux conditions. The optical fiber probe is applied to measure the multi-dimensional distribution of local bubble parameters, so that an integrated database for the two-phase flow variables in the boiling flow channel can be obtained. The local distributions of void fraction, bubble velocity, bubble arrival frequency, and the interfacial area concentration (IAC), Sauter mean diameter were measured under four sets of test conditions.

2. Experiments

2.1. Test facility

The schematic diagram of the test section is shown in Fig. 1. The heater rod of 10 mm in O.D. and 2.0 m in effective height was installed along the centerline of a vertical tube of 30 mm in O.D. The heater rod has the maximum capacity of 24 kW, which is capable of supplying the heat flux up to 382 kW/m^2. Four 0.5-mm-O.D. thermocouples were installed to measure the wall temperature of the heated surface.

In order to visualize the flow structures in the test section, the visualization windows were installed at the positions of L/D_h=34, 59, 84 from the inlet. The fluid temperature and local bubble parameters were measured at four elevations (L/D_h= 21.5, 46.5, 71.5, 100).

The test section was connected to the JNU boiling test facility. The loop consists of the main tank, pump, preheater, separator, condenser, heat exchanger as shown in Fig. 2. The de-mineralized water was used as a working fluid. The flow rate of the test section is measured by the Coriolis mass flowmeter installed between the preheater and the test section.

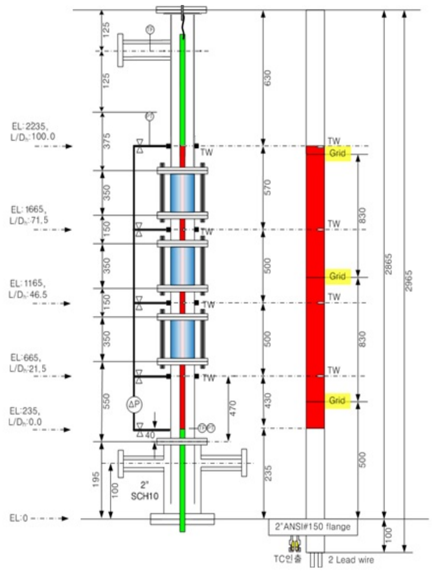


Fig. 1. Schematic diagram of the test section

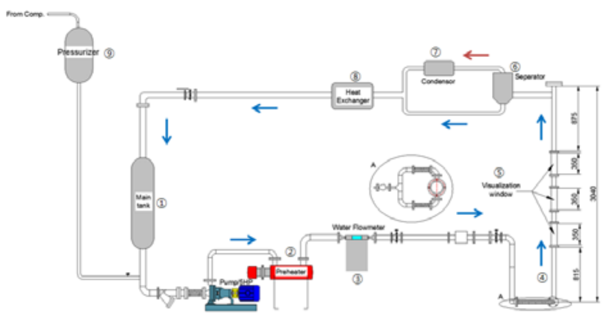
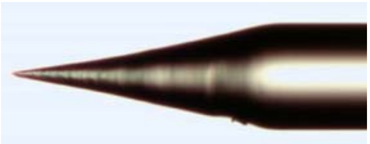


Fig. 2. Forced-convective boiling test facility in JNU

2.2. Measurement of bubble paramters

In this study, the local bubble parameters were measured by using the optical fiber sensor manufacture by *A2 Photonic Sensors*. Its principle relies on measuring the reflection of a laser beam at the interface between the probe tip and the surrounding phase. The quantity of light that is reflected back into the probe is determined by the refractive index of the medium surrounding the sensing part of the probe.

Figure 3(a) presents the sensing tip of the probe. The outer diameter of the optical fiber is 125 microns, and the tip of the cone is about 1-micron wide. The optical fiber, surrounded by the stainless steel tube, is mounted on the traversing mechanism shown in Fig. 3(b) so that the position of the probe tip was traversed precisely in the radial direction of the annulus. In the test, the bubble parameters were measured at around 10 radial positions in the annulus. Since the test section is equipped with four sets of the optical fiber probe, the multi-dimensional distribution of bubble parameters could be achieved in a CFD scale.



(a) Sensing tip

(b) Traversing apparatus

Fig. 3. Optical fiber probe for measuring bubble parameters

2.3. Test matrix

In this study, the experiments were conducted at relatively low-heat flux and low-flow rate conditions compared to the test conducted by Yun et al. [1]. In the experiments, the flow conditions were set for the heat flux of 370 kW/m^2, the mass flux of 430 ~ 680 kg/m^2s and the inlet subcooling of 12 ~ 18 K at pressure of 114 ~ 152 kPa. The test matrix is summarized in Table 1.

Table 1. Test matrix for subcooled boiling test

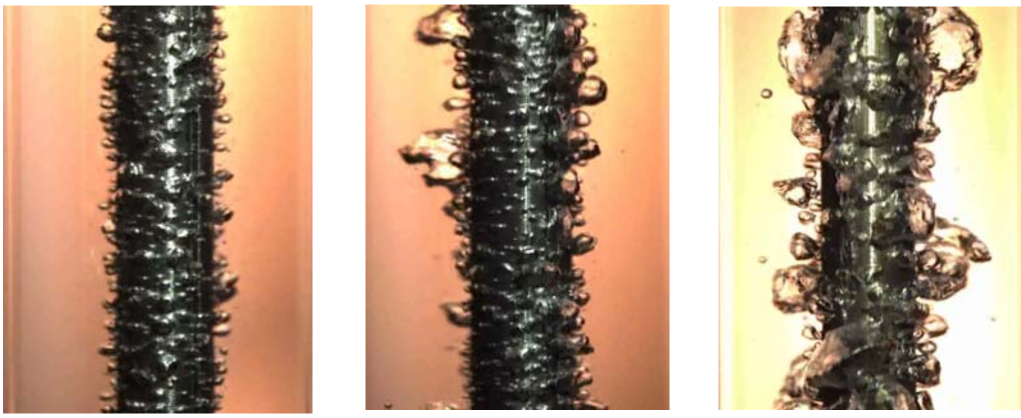
Test	Heat flux (kW/m^2)	Mass flux (kg/m^2s)	Inlet subcooling (K)	Outlet pressure (kPa)
Run 1	375.6	668.5	15.59	114.3
Run 2	377.2	684.4	12.36	123.0
Run 3	369.2	684.4	14.25	133.5
Run 4	372.4	429.7	17.57	151.9

3. Results and Discussions

By using the high speed camera, the behavior of bubble nucleation, sliding, coalescence, departure, and the condensation near the boiling surface was observed at three elevations. Figures 4 shows the visualization result of the bubble behavior in the preliminary run conducted when the heat flux is 366.1 kW/m^2, the mass flux is 636.6 kg/m^2s, and the inlet subcooling 17.2 K. The complicated behavior of vapor bubble near the heated surface were recorded. In particular, it was observed that generated bubbles slid along the wall, without departing immediately after nucleation, and merged with new ones on a pathway to form larger bubbles. It seemed as if the nucleation site density was degraded by the movement and coalescence of bubbles.

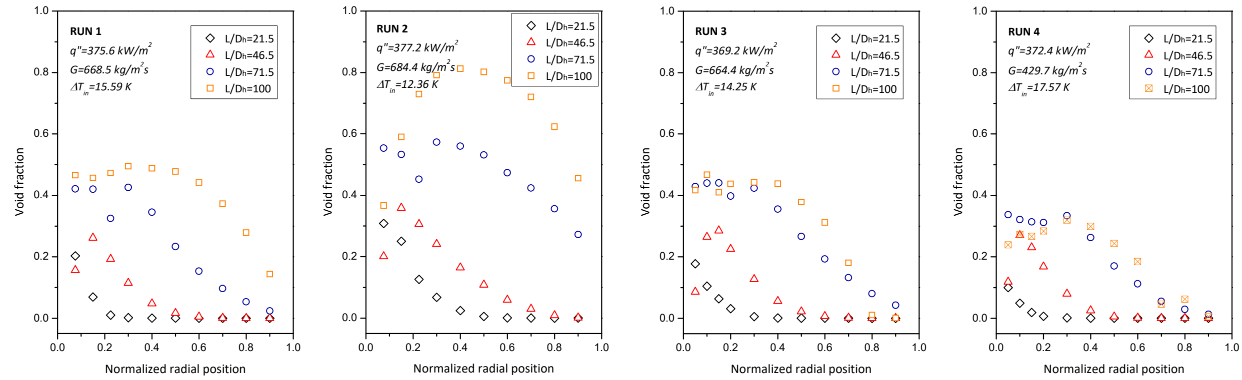
The measurement results of the local void fraction for four test runs are depicted in Figs. 5. Note that the propagation of the void fraction is affected not only by the bubble generation rate from the wall, but by the non-drag forces acting on the bubbles and the coalescence / breakup (or condensation) characteristics.

In all cases, the local void fraction increased as the two-phase mixture moved upwards, and thus heated more. The bubble boundary layer was grown as the heated length augmented; it covered the entire cross-sectional area of the channel at the elevation L/D_h= 71.5.



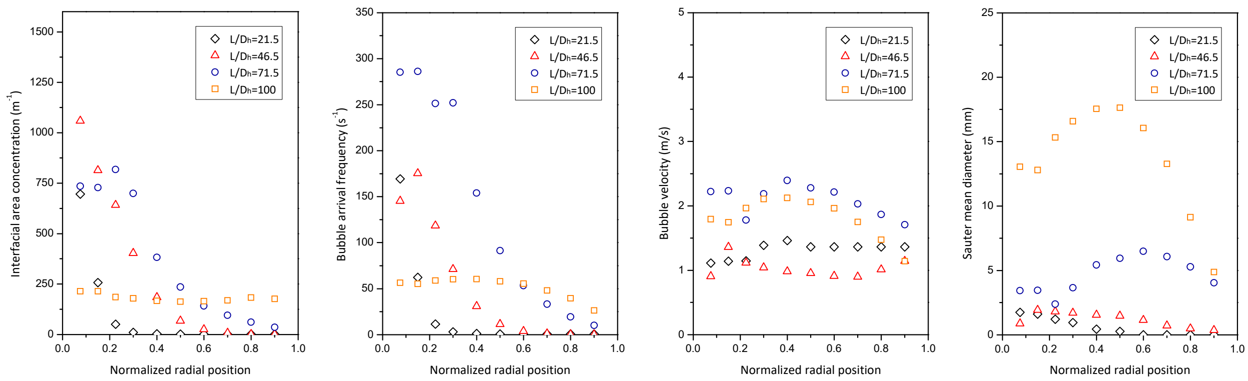
(a) L/D_h=34 (b) L/D_h=59 (c) L/D_h=84

Fig. 4. Visualization of the bubble behavior in subcooled flow boiling
(heat flux: 366.1 kW/m^2; mass flux: 636.6 kg/m^2s; Inlet subcooling 17.2 K)



(a) Test run 1 (b) Test run 2 (c) Test run 3 (d) Tet run 4

Fig. 5. Propagation of the local void fractions in the subcooled flow boiling tests



(a) IAC (b) Bubble frequency (c) Bubble velocity (d) Sauter mean diameter

Fig. 6. Measurement results of local bubble parameters in Test run 1

With regard to the radial profile of the void fraction, at the lowest measuring point (L/D_h= 21.5), the void fraction showed the peak value the heated wall, while it decreased monotonically away from the surface. On the other hand, as the two-phase mixture flowed upwards, the point where the void fraction is maximum shifted to the center of the flow channel.

Generally, the radial migration of bubbles is influenced by non-drag forces such as the turbulent dispersion force, the lift force, and the wall lubrication force. Among them, the lift force plays a dominant role in determining the radial profile of the void fraction.

The lift force applied to the direction of the wall when the size of a bubble is smaller than a critical value, while it acts to push bubbles to the center of the flow channel when the bubble diameter exceeds the critical value. That is, the generated bubbles coalesce into larger ones as they heated along the wall, and thus the direction of the lift force was changed as the steam-water mixture flows.

The measurement results of local bubble parameters in the Test run 1 were depicted in Fig. 6. Besides the local void fraction, the radial distributions of the IAC, the bubble arrival frequency, the bubble velocity, and the Sauter mean diameter were measured. Details will be discussed in the presentation at the conference.

4. Conclusions

In this study, the local bubble parameters in steam-water subcooled boiling flow were measured in a vertical channel at low heat and mass flux conditions. An experimental DB for bubble parameters were obtained through four sets of test program. These test data can be used to validate the physical model of wall boiling and non-drag forces for vapor phase in a CFD-scale codes.

ACKNOWLEDGEMENT

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