Experimental study of conjugate heat transfer associated with single bubble boiling

Iljin Kim [a], Hyungdae Kim [a*]
[a]*Department of Nuclear Engineering, Kyung Hee University, Republic of Korea*
[*]*Corresponding author: hdkims@khu.ac.kr*

1. Introduction

Nucleate boiling has been widely used in practical industrial filed due to its high cooling capacity. Nuclear power plants also have a close relationship with nucleate boiling even in normal operation, transient and accident situations. Accordingly, research related to the heat transfer mechanism and characteristic analysis of nuclear boiling has been continuously conducted to evaluate the safety of nuclear power plants.

Jung et al. analyzed the structure of the bubbles, microlayer and heat transfer phenomenon through the heated wall using the visualization techniques to evaluate contribution of the microlayer to the growth of the bubbles [1]. In a subsequent study, a comparative analysis was performed between the experiment and the boiling computational code for the heat transfer phenomenon through the heated wall [2]. Chung et al. analyzed the geometry of the microlayer and the local wall heat flux, evaporation heat flux of microlayer and conduction through microlayer were compared [3].

Jung et al. conducted nucleate pool boiling experiments with various wall orientation to evaluate the effect of wall orientation on the heat flux partitioning model and correlations [4].

In the previous studies, the heat transfer characteristics during the existence of the microlayer was well analyzed by comparing wall, evaporation and conduction heat fluxes of the microlayer region.

However, the previous research focused on the heat transfer characteristics due to microlayer, the evaluation of quenching heat transfer which is another major heat transfer mechanism caused by the rewetting of the fluid due to bubble departure process was insufficient.

In this paper, quantitative evaluation of heat transfer mechanisms during a bubble period was conducted by analyzing the behavior of bubble and microlayer, and heat transfer characteristics through the heated wall in saturated nucleate pool boiling condition.

2. Experiment

2.1 Experimental setup and test sample

As a test substrate, a cylindrical CaF_2 with a diameter of 50 mm and a thickness of 100 mm was used. Indium-Tin-Oxide (ITO) was deposited on the top side of test substrate with an area of 8×15 mm^2 and a thickness of 700 nm. Pt was deposited at both ends of ITO to heating by applied voltage. Immersion heaters were installed in the pool to maintain the fluid at a saturation temperature and its temperature was measured by T-type thermocouple. The test sample is located at the bottom of the pool. The high-speed camera video (HSV) was installed at the side of pool to visualize the bubble geometry. Another HSV camera was used to detect the liquid phase distribution on the boiling surface using the total reflection (TR) technique. The infra-red (IR) camera was used to measure the temperature distribution at the bottom of ITO film. The HSV cameras and IR camera were synchronized temporally. The liquid phase distribution and wall temperature distribution were able to spatially map by capturing a reference dots around ITO film. The frame rates of HSV and IR cameras were at 50 kHz and 1 kHz, respectively.

2.2 Calculating wall heat flux distribution

The temperature distribution of heater surface was used to calculate internal temperature of test substrate and heat flux distribution of heater surface using a commercial computational fluid dynamics program (ANSYS Fluent [6]). The temperature distribution was used time-varying temperature boundary condition at top side of test substrate using a user define function which is able to update the temperature distribution. The adiabatic boundary condition was set to the other sides of the substrate.

2.3 Experimental condition

The experimental data were obtained for single bubble nucleate boiling of deionized water (DI) and applied heat flux was 114 kW/m^2 in a saturated condition under atmospheric pressure.

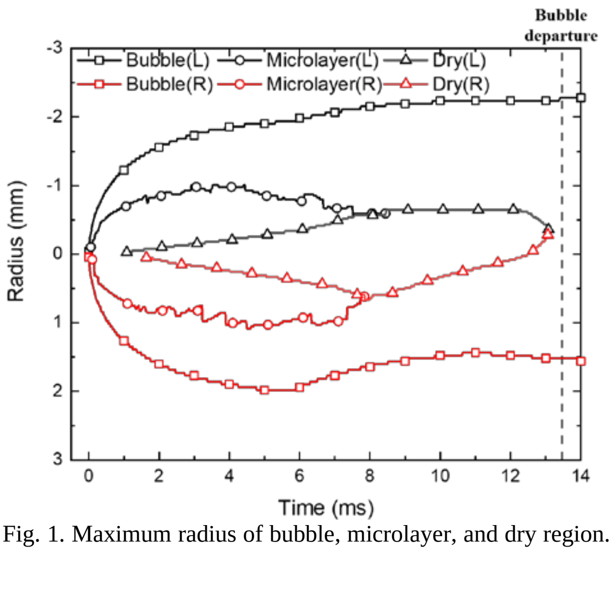

Fig. 1. Maximum radius of bubble, microlayer, and dry region.

3. Results and Discussions

3.1 Behavior of Bubble, microlayer, and dry region

Just after nucleate boiling occurs on the heated surface, it was observed that the bubble and microlayer rapidly grew in the radial direction. As time goes, the expansion rate of bubble in the radial direction decreased. The microlayer was fully grown in the radial direction at 4-5 ms, and it was fully depleted around 8 ms. On the other hand, the dry region was extended at a slower rate than the microlayer in the radial direction, and the maximum radius of the dry region was about 40% of microlayer. The bubble began to bias to the left due to the nucleation of bubble on the right from 6 ms. Therefore, the time which the microlayer was completely depleted was different from the left and right sides. In addition, the maximum radius of the dry region was almost fixed on the left side, while the dry region was decreased until bubble departure on the right side.

3.2 Heat transfer mechanisms

Fig. 2 shows the geometry of bubble and microlayer, and heat flux distribution on heater surface, and the internal temperature distribution of heater substrate. At 5.84 ms when the microlayer still existed beneath the bubble, the temperature drop in the substrate is observed because of microlayer evaporation. However, the temperature of dry region begun to recover because there is no more evaporation of microlayer in dry region. Because of low temperature rather than the surrounding substrate, the temperature of dry region getting rise due to heat conduction in the substrate.

The microlayer is fully depleted, and bubble was in departure process at 10.84 ms. The triple contact line had been moved toward center of bubble. The triple contact line of right side was located around the nucleation site, but the left side was located quite far from the nucleation site. As a result of location of triple contact line, lower temperature area of heated surface on the left side is still in the inside of bubble but the right side is rewetted by surrounding liquid. So quenching heat transfer occur at the right side of triple contact line. But there is a heat transfer even in the dry region which is caused by temperature difference of substrate. The heat transfer mechanisms are different with left and right, but its magnitude is quite similar. So, it is important to evaluate heat transfer mechanism with geometrical information of bubble and microlayer, and temperature distribution of heater substrate.

3. Conclusions

In this paper, geometry of bubble, microlayer and dry region were obtained by analyzing the bubble behavior using total reflection and laser interferometry. Heat transfer phenomena was also analyzed with wall temperature distribution of heated surface. With these information, quantitative evaluation of heat transfer mechanisms during a bubble period was conducted. The internal temperature of substrate is also analyzed with geometrical information and heat flux distribution. In the early stage of bubble growth, it confirmed that the main heat transfer mechanism is evaporation of microlayer. However, the heat transfer mechanisms are different with left and right of bubble, but its magnitude is quite similar. So, heat transfer mechanism should be determined with considering geometrical information and temperature distribution of heater substrate.

ACKNOLEDGEMENT

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. 2018M2B2A906584122).

REFERENCES

[1] Satbyoul Jung and Hyungdae Kim, Simultaneous investigation of dynamics and heat transfer associated with a single bubble nucleate boiling, Transactions of the Korean Nuclear Society Autumn Meeting, 2013.
[2] Satbyoul Jung, Yasuo Ose, Hyungdae Kim and Tomoaki Kunugi, A comparison study of experimental and direct numerical simulation results associated with dynamics and heat transfer of a boiling bubble, Transactions of the Korean Nuclear Society Autumn Meeting, 2014.
[3] Seunghyuck Chung, Satbyoul Jung, and Hyungdae Kim, An Experimental Study on Heat Transfer Mechanisms in Microlayer of a Boiling Bubble, Transactions of the Korean Nuclear Society Autumn Meeting, 2014.
[4] Satbyoul Jung, and Hyungdae Kim, Study on Effects of Orientation on Wall Boiling Heat Flux Partitioning, Transactions of the Korean Nuclear Society Autumn Meeting, 2014.

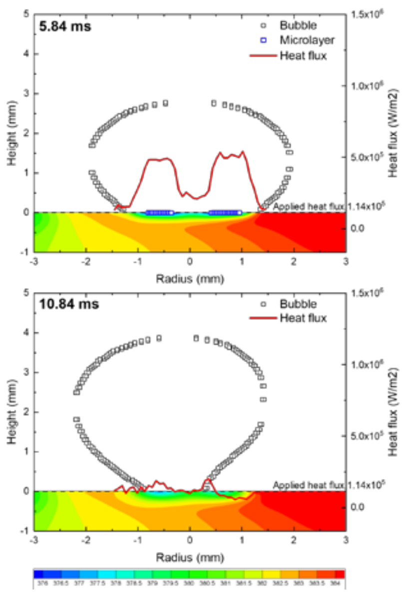

Fig. 2. Geometries of bubble and microlayer, and heat flux distribution on heated surface, and internal temperature distribution of substrate at 5.84 ms and 10.84 ms respectively.