High-fidelity imaging of a vapor bubble growing in subcooled flow boiling using synchrotron X-ray and LED interferometry

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1. Introduction

Subcooled flow nucleate boiling is crucial thermal-hydraulic phenomenon that occurs in a hot channel during normal operation of a PWR. To anticipate thermal-hydraulic interactions between the nucleating bubbles and the fuel cladding and predict the resulting temperature distribution of the cladding surface, understanding and modeling the phenomena are essential for safety of nuclear reactors. Recently, thanks to the rapid development of computer technology, such as the interface tracking technique that simulates the actual interface of a bubble in 3-D and direct numerical simulation that directly calculates the Navier-Stokes equation without a turbulence model [1-2], realistic simulation of flow boiling phenomenon using high-resolution computational fluid dynamics tools has become feasible. Since these analysis techniques directly simulate the phase change between the liquid-gas phase interface, they are very sensitive to the grid size. Therefore, visualization experimental data with the time and space resolutions corresponding to the grid size used in the simulation are required for accurate validation.

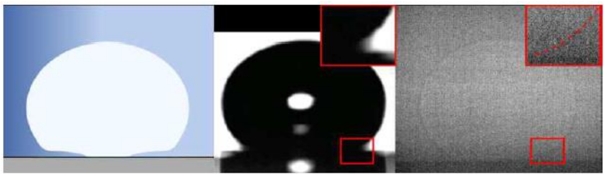

Fig. 1. Conceptual diagram of a boiling bubble (left), visualization image using visible light (middle), visualization image using synchrotron x-ray (right)

Synchrotron x-ray is a type of x-ray generated from a synchrotron radiation facility, which is a large circular particle accelerator that uses strong magnetic fields to accelerate electrons to nearly the speed of light. The imaging technique using synchrotron x-rays enables to capture highly precise interfaces of boiling bubbles without distortion due to diffraction. Figure 1 shows a comparison between typical images of a single boiling bubble using visible light and synchrotron x-ray. Compared to visible light, synchrotron x-rays have less diffraction at apparent triple contact point due to its shorter wavelength, so that more precise interface can be obtained.

In this study, an imaging experiment was conducted using the synchrotron x-ray source of Pohang Accelerator Laboratory PLS-II 9D beamline. However, the data using synchrotron x-ray has a limited scope of use as data to verify interface tracking CFD analysis results because it is impossible to quantitatively grasp detailed structures beyond the vicinity of the apparent contact point which is a liquid film so-called microlayer. To overcome this limitation, interferometry with a LED light source was additionally applied [3].

2. Experiment

The experimental apparatus mainly consists of a flow loop and a boiling test section.

2.1 Flow Loop

Boiling bubbles were generated at atmospheric pressure, subcooling of 5 ℃ and mass flow rate of 212 kg/m^2-s. Figure 2 shows a schematic diagram of the loop. The experiment apparatus is modularized and miniaturized so that it can be easily installed in a narrow beamline field.

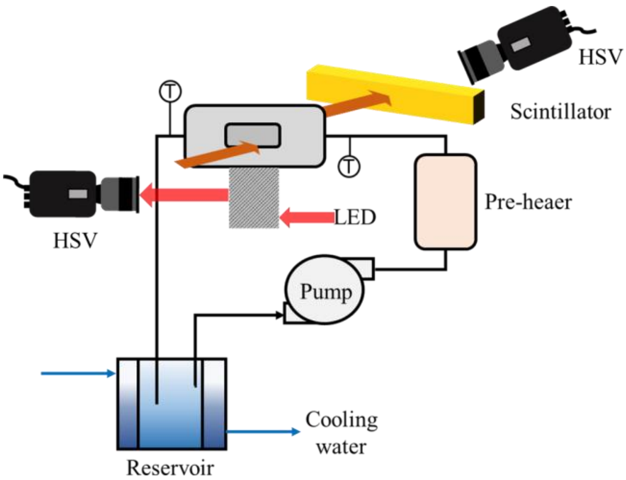

Fig.2. Schematic of the experimental flow loop.

2.2 Boiling test section

Figure 3 shows a 3-D drawing of the boiling test section. To minimize attenuation of the incident x-ray into the side wall of the test section, PEEK with a low attenuation coefficient was chosen. To generate boiling bubbles by means of electrical Joule heating, thin ITO (indium tin oxide) film was deposited on a B270 glass substrate. The glass substrate and the ITO heater are

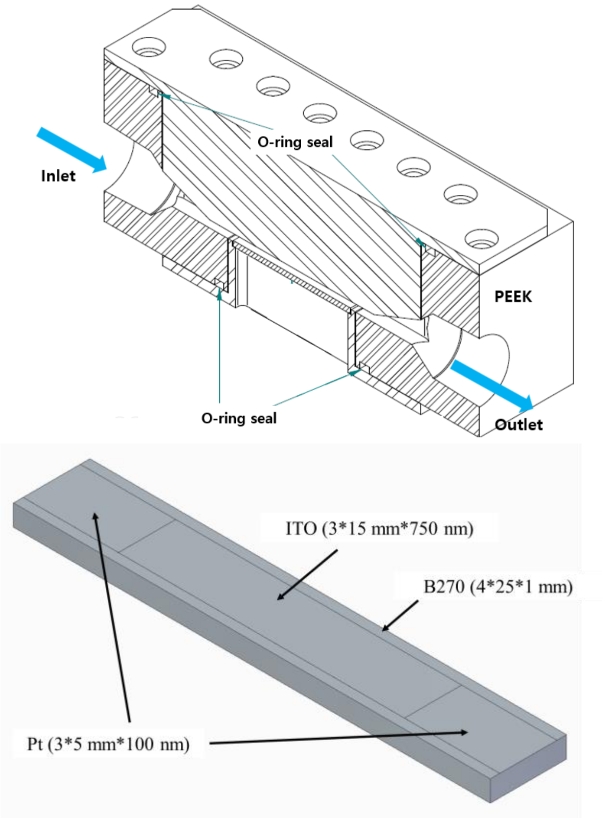

Fig.3. Conceptual diagram of the boiling test section.

transparent to visible light so that interferometry using LED can be applied from below.

The width of the ITO thin film was determined to be 3 mm considering the size of steam vapor bubbles in flow boiling under atmospheric pressure.

3. Result and Discussion

Figure 4 is an image showing the process of generation, growth, and departure of bubbles over time taken using synchrotron x-ray. It was obtained at the heat flux of 183 kW/m^2 and with imaging conditions of 5000 fps and exposure time of 100 μs. Bubble generation was observed at 0.2 ms, but the initial growth rate was too fast to clearly capture the interface. After 0.4 ms, the interface was clearly observed because the bubble growth rate decreased. The initial boiling bubble grew axis-symmetrically, but over time, it grew inclined in a deflected shape by the flow direction. The grown bubbles departed from the nucleate boiling spot at 1.2 ms and disappeared on the heating wall at 1.6 ms.

Figure 5 shows the lateral diameter and height of bubble. The bubble tended to have a higher aspect ratio (height /lateral diameter) than that of bubble under pool boiling condition. The difference was attributed to the liquid flow. The image using synchrotron x-ray show relatively little distortion that even the triple contact line of the bubble could be distinguished.

Figure 6 is an image showing the fringe pattern at the bottom of the flow boiling bubble over time taken using LED interferometry, which was performed at the same

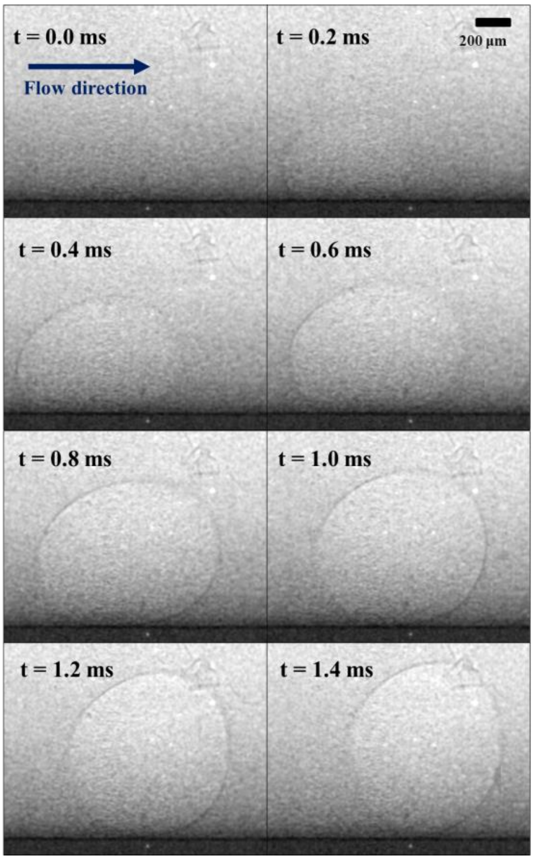

Fig.4. Series of bubble growing image data using synchrotron x-ray.

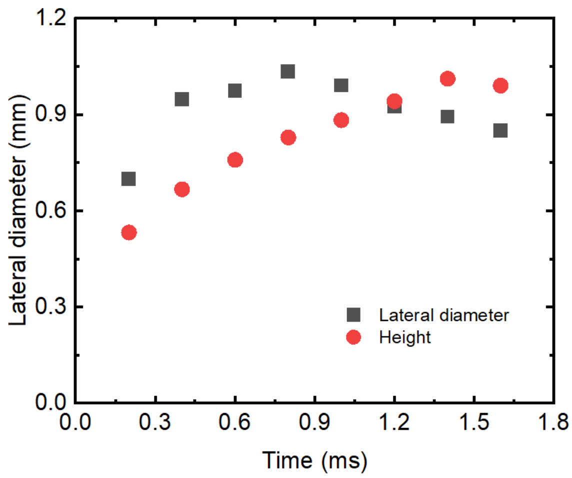

Fig.5. History of lateral diameter and height of a vapor bubble.

imaging condition of 5,000 fps and exposure time of 100 μs.

In the initial stage of bubble generation, fringes in the shape of concentric circle were observed, but after the bubbles were affected by the flow (1.0ms ~), it was observed that the fringes tilted in the flow direction.

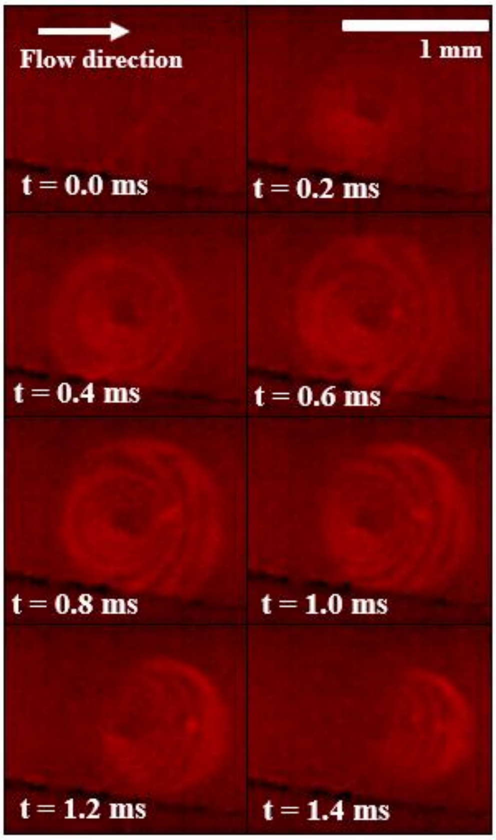

Fig.6. Series of bubble growing image data using LED interferometry.

4. Conclusion and Further work

In this study, the behavior and shape of a single boiling bubble in the subcooled flow boiling condition were visualized at high resolution using synchrotron x-ray in Pohang Accelerator Laboratory and LED interferometry. A single boiling bubble generated in the test section was observed and analyzed by designing an experimental apparatus optimized for simultaneous application of the two measurement techniques.

As future works, clear bubble interface data should be obtained for various quantitative analyses. From the data, whole bubble geometry from micro to macro scale will be analyzed to model the thermal and dynamic interaction with wall under flow boiling situation.

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