Observation of Departure from Nucleate Boiling under Flow Using Optical Visualization and IR thermometry

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1. Introduction

Departure from nucleate boiling (DNB) is one of main limiting phenomena in the safety of a nuclear reactor. For the prediction of critical heat flux at DNB, several mechanistic models have been suggested. Well-known mechanistic models include hydrodynamic instability, macrolayer dryout, hot/dry spot, and interfacial lift-off model [1]. These mechanistic models were developed by direct observing of flow structure and liquid film on boiling condition.

Recent visualization studies of the irreversible dry patch generated by the evaporation of the liquid film that exists under the elongated bubble have been carried out through the development of the visualization experiment technique, and these studies suggest a new perspective on the DNB mechanism. For better understanding, visual and thermal observation on the dry patch has been conducted enabling better knowledge on the underlying mechanism and measurement of individual parameters for mechanistic models [2-4]. In our research, we closely examined the phenomenon of rewetting failures of dry patches during DNB to provide a deeper understanding of the mechanism of DNB, and to assist in subsequent mechanistic modeling.

2. Methods and Results

2.1 Experiment Loop Setup

We set up a water flow loop under atmospheric pressure (Fig. 1). The loop includes a rectangular test section comprised of an ITO (Indium tin oxide) heater coated on a sapphire substrate. The cross sectional size of the flow channel was 1.5 cm by 1.5 cm and the ITO heater was 1 cm wide and 12 cm long. The long length of the ITO heater enabled development of coagulated bubbles upstream of the DNB location. The mass flux and sub-cooling degree were 250 kg/m^{2}s and 8 °C, respectively.

To observe the boiling surface, two high-speed cameras and one infrared (IR) camera were installed with lighting systems (Fig. 2). One high-speed camera recorded the side view of the channel focusing on the bubble structures. The other high-speed camera recorded total internal reflection images. The IR camera recorded the radiation counts on the ITO heater surface. Images from IR camera were synchronized spatially and temporally. The spatial resolution and frequency of measurement were in the range of 70 ~ 120 μm and 1.0 ~ 2.5 kHz, respectively.

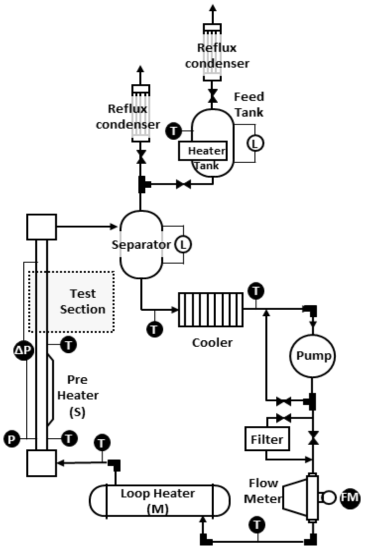

Fig. 1. Schematic for the DNB test loop

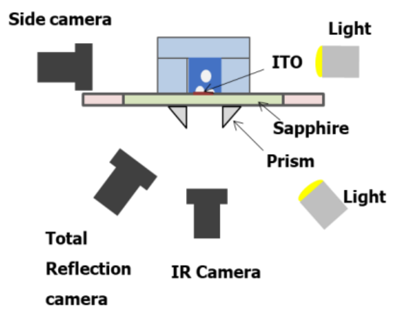

Fig. 2. Arrangement of cameras around the test section (top view)

2.2 IR thermometry preparation

The process of converting the radiation counts obtained from the IR camera to temperature and heat flux needs special attention. Since the temperature profile through the sapphire can have a large effect on evaluating the accuracy of the temperature at the ITO heater surface, we calculated both radiation and conduction along sapphire. Therefore, a coupled radiation-conduction equation was solved.

For determination of the reflectivity at the heater-sapphire interface, a separate test was conducted using a block heater. A thermocouple was installed between a block heater and a sapphire to get the temperature at the ITO (Fig. 3). Measured counts from the IR camera were compared with the theoretical temperature-count curve. As a result, the reflectivity was found to be 0.5.

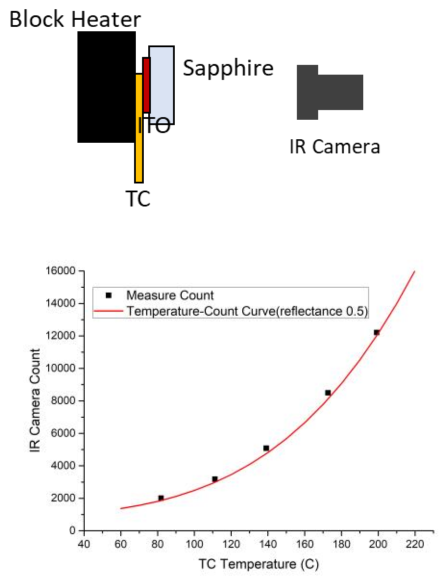

Fig. 3. Setup (top) and results (bottom) for calculation of sapphire-ITO reflectivity

2.3 Observation of DNB

In our experiment condition, slug flow was observed. Elongated bubbles were formed intermittently. The behavior of elongated bubbles and dry patches at the DNB condition was examined using the side view, total reflection view, temperature profile and heat flux profile (Fig. 4). Passage of a large elongated bubble enabled formation and growth of a dry patch once the microlayer under the bubble was evaporated. Figure 5 represents the maximum temperature trend of the ITO heater. Until water slug was supplied from the upstream, the temperature of the dry patch increased. The water slug could rewet the dry patch even when its maximum temperature reached 250 °C. However, when its temperature increased beyond 250 °C, the water slug failed to quench the dry patch, leading to DNB. Detailed analysis is on-going in terms of the dry patch shape and temperature profile.

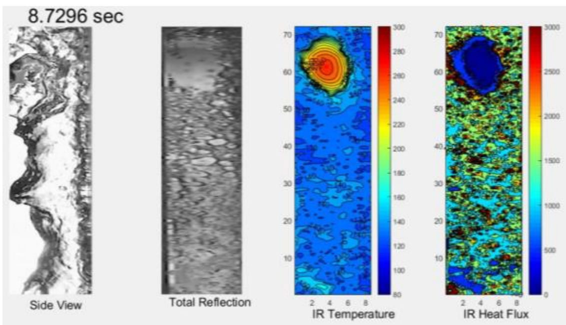

Fig. 4. Side view, total reflection view, temperature profile, and heat flux profile (from left to right)

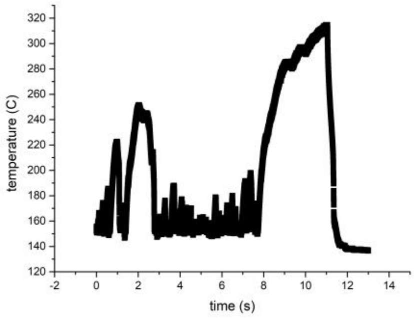

Fig. 5. Trend of the maximum ITO temperature

3. Conclusions

To explore the mechanism of departure from nucleate boiling, optical visualization - side view, and total reflection- and IR thermometry were utilized. These techniques were applied to a DNB test loop, where upward flow was made at a predetermined inlet temperature and flow rate at atmospheric pressure. The recorded data were synchronized spatially and temporarily. As a result, we observed the formation of dry patches and their temperature rise. Some dry patches reached even up to 250 °C before being quenched again. More analysis is being made to leverage the recorded data from total reflection and IR thermometry data.

Acknowledgment

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