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Mechanism study of departure of nucleate boiling on forced convective channel flow boiling

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ABSTRACT

We carried out a visualization study of Departure from Nucleate Boiling (DNB) of a vertical upward flow boiling condition. In order to evaluate the effects of the convective flow condition on the DNB mechanism, we synchronized three high-speed cameras (bottom view, side view and total internal reflection view) and captured the detailed dry patch dynamics and relevant bubble behavior. A convective flow of 250 kg/m^2 s and subcooled 5 °C (water) was controlled on a heating surface (10 mm × 120 mm), which is much larger than the Rayleigh-Taylor instability wavelength (approximately 25 mm). As a brief result, a high heat flux near DNB (1000 kW/m^2) produced periodic massive elongated bubbles through numerous bubble coalescence, and a thin liquid film was developed on the heater surface. Local evaporation of the thin liquid film generated a dry patch, which was observed using a total internal reflection technique. Accounting for the dry patch size and lifetime, the local overheated condition of the dry patch was discussed as an important physics of the irreversible dry patch (DNB). This study may provide a deep insight for understanding the DNB mechanism on the relatively low mass flow boiling condition.

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1. Introduction

The boiling limit, which is a technical ending point of a boiling heat transfer application, has attracted lots of attention due to not only its engineering importance but also its own academic interest. While the engineering and industry field call it a boiling crisis or boiling limit, a research group discussed it as a critical heat flux (CHF) or departure from nucleate boiling (DNB). Although there are several notations by their usages in engineering works or an interpretation of the boiling curve, they have a common point with respect to a phenomenological description. As a vapor blanket covers on boiling surface, the dried surface has no more nucleate boiling chances. Then, the temperature sharply increases through the thermal insulating vapor layer. In this article, the author would like to use the term “DNB” as the key physics. During the last several decades, numerous mechanistic models of DNB have been introduced, and the methods of DNB enhancement have been reported from an engineering viewpoint.

Several studies of the DNB mechanism will be introduced to provide a simple motivation of this study, as follows. First, Zuber and Kutateladze elucidated the DNB triggering mechanisms through the hydrodynamic instability analysis of the liquid–vapor interface [1–3]. Vapor columns of a massive bubble structure become unstable and collapsed by a mis-force balance between the upward vapor flow and downward liquid momentum, which is called Kelvin-Helmholtz instability. This instability of the liquid–vapor interface triggers a pre-required condition of vapor insulating layer formation, as an onset of DNB. While the instability models interpreted the boiling phenomena with a bulk scale of the physical parameters, i.e., a massive bubble size and vapor column, later models (1980 s) analyzed more detailed aspects of DNB mechanisms with sub-millimeter or micrometer scaled parameters. For example, Haramura and Katto suggested that a dryout of the hypothetical liquid layer beneath massive vapor mushroom, called macrolayer, is a prerequisite of the DNB mechanism [4]. Based on this sublayer dryout model, a variety of the hydrodynamic analysis about the liquid layer dryout has been reported [5–8].

As the experimental observation techniques improved and analytical modelling works became more sensitive in terms of temporal and spatial resolution, a detailed description of the DNB mechanism was provided after the 1990s. Unal et al. divided the macrolayer region into a dried area (dry patch) and two-phase region, and they discussed the thermal behavior of each regions during a vapor mushroom cycle [9]. As the temperature of the

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Nomenclature

T	temperature [K]
t	time [s]
q''	heat flux [kW/m^2]
C_P	specific heat capacity [J/kg·K]

Greek symbols

ρ	density [kg/m^3]
δ	substrate thickness [m]

dry patch center increases to the Leidenfrost condition, DNB is established. In addition, Ha and No also introduced the concept of nucleation activity surrounding a dry patch as a key physics of the DNB mechanism. They presented a semi-analytical model, called a "hot and dry spot model" of the nucleation activity under the macrolayer. This suggests that sufficient nucleate boiling activities surrounding the dry spot are responsible for the hot spot events (DNB). Theofanous applied an infrared visualization technique to observe the thermal behavior of the dry patch near the DNB condition. They also reported the reversible behavior of the dry patch with a rewetting event [10]. A dry patch precedes several cyclic dynamics, called a reversible dry patch, and eventually, an irreversible dry patch takes place. Recently, the cyclic dry patch and irreversible critical condition were discussed using Total Internal Refection Visualization [11–14]. According to the various visualization studies, it is recommended to discuss the force competition between the dry patch formation and the rewetting momentum for understanding the DNB mechanisms.

Under a convective flow environment, it generally has a more complex bubble structure owing to various flow patterns. The critical heat flux predictions rely far more on an empirical correlation of the flow conditions than the pool boiling cases introduced above [15,16]. Regarding the modelling work, several conceptual modifications of the previous hydrodynamic model and macrolayer model have been reported [17,18]. On the other hand, Weisman and Pei depicted crowding bubbles near the wall as a key parameter of DNB. [19–21] When highly dense bubbles near the boiling surface is developed in over a 0.82 void fraction, the bubble layers can block the enthalpy exchange between the wall and bulk flow and trigger a DNB. This concept and the critical value of the void fraction have still been adopted in a variety of numerical simulations for transition boiling and film boiling condition owing to its simple scheme.

In this study, the effects of the convective flow condition on the dry patch dynamics and DNB mechanism were investigated, as a successive study of our previous discussion (Chu et al. [13]). First, we prepared a flow boiling experimental loop having a one-sided vertical heating test section for D.I. Water and convective conditions ($\sim$250 kg/m^2 s). To observe bubble structures and dry patch dynamics simultaneously, we installed synchronized and multi-viewed cameras that consist of bottom-viewed, side-viewed and bottom-viewed total internal reflection images. It was revealed that elongated massive bubbles play an important role in the dry patch growth. This study on the dry spot dynamics, and relevant thermal-hydrodynamic principles under the flow boiling conditions, may provide an important insight into the DNB mechanism under low mass flux conditions.

2. Experiments

2.1. Flow boiling loop

Fig. 1(a) shows a schematic diagram of the experimental flow loop system in this study. The schematic diagram introduces several loop components and supports accessory parts. First, the main loop flow was driven by a pump, and the flow was heated by two preheaters for the degassing process. The dissolved gases were released at the separator, maintaining the saturated flow conditions. The reflex condenser condensed the steam flow and controlled the total water capacity in the flow loop. Simultaneously, the feed tank also took a degassing process for 2–3 h. After the degassing process, the separator was linked to the feed tank, and the valve to the separator's reflex condenser was closed. As the feed tank maintained saturation conditions, the dissolving process to the main loop flow was blocked. Then, the main loop flow's subcooled condition could be controlled by manipulating the inlet temperature of the test section (about 5 °C of subcooled). The main preheater controlled the overall heating level, and the sensitive inlet temperature was regulated using a small pre-heater (see Fig. 1 (a)). The mass flow rate and pressure range were measured using a flow meter (RHENIK, RHM08A1) and absolute pressure gauge (3051CD3A), respectively. The main flow has a relatively low mass flux condition (250 kg/m^2 s) and near atmospheric pressure. In addition, nine points of temperature of the loop and pressure loss in the test section part were tracked. After the above preparation, the main power source (DC 1000 V-30 A) supplied an electric power on the test section (Joule Heating method). Reaching a high heat flux condition, we visualized the dry patch dynamics using three synchronized high-speed cameras. The DNB is tracked through the real-time imaging of the total internal reflection view, and we shut down the main power supply with the occurrence of a meaningful dry patch size to prevent the test sample burnout and failure. Accounting for all instrument errors, the estimated maximum uncertainties of the inlet temperature, heat flux, and mass flow rate were 0.64 °C, 5.92 kW/m^2, and 10.98 kg/m^2 s, respectively, over the expected DNB range

2.2. Test section design

Fig. 1(b) shows a design of the joule heating method on the test section. To visualize the bubble structure from multiple view points, a transparent substrate (80 mm × 180 mm, 0.5 mm thickness), sapphire, was prepared. As the heating material, an ITO (Indium Tin Oxide) layer (10 mm × 120 mm) was coated on the sapphire substrate using a sputtering process. In this study, the ITO layer is approximately 10 O/sq. Since the ITO layer also has a transparent feature, a couple of studies have reported its application on a visualization study of multiphase systems. Compared to previous studies [11–14], the present research shows a much longer heating length, which is three or four times the critical wavelength of a Rayleigh-Taylor instability analysis (approximately 25 mm of saturated water). Two Pt layers (Platinum, 100 nm) were deposited on the edge of the ITO layer, and the copper blocks were soldered on the Pt layers (see Fig. 1(b)). Electrical power was supplied through the electrode system. The test section channel (15 mm × 15 mm) is made of poly-carbonate, which is also transparent, as shown in Fig. 2. The boiling surface is the opposite side of the ITO coated surface. Because all four sides of the test

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