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Simultaneous observation of dynamics and thermal evolution of irreversible dry spot at critical heat flux in pool boiling

Dong Eok Kim [a], Junkyu Song [b], Hyungdae Kim [b,*]

[a] *Department of Precision Mechanical Engineering, Kyungpook National University, Sangju, Republic of Korea*
[b] *Department of Nuclear Engineering, Kyung Hee University, Yongin, Republic of Korea*

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ABSTRACT

It is generally accepted that the dry area underneath growing bubbles plays a vital role in understanding and modelling nucleate boiling heat transfer phenomena, including the critical heat flux (CHF). This study presents an investigation of the nucleate boiling phenomena under various surface heat flux conditions using a high-speed infrared thermometry technique called DEPIcT. The observation results for the liquid–vapour phase distribution on a boiling surface showed the formation, coalescence, and dynamic behaviours of dry spots on a boiling surface, and as the surface heat flux increased, the frequency and density of the dry spots significantly increased. Intensive nucleation behaviour near the triple contact line of a dry spot interrupting the wetting of the liquid was observed at a high heat flux. The liquid–vapour phase distribution and the temperature evolution of the dry spot area indicated the existence of an irreversible dry spot, which leads to surface overheating and consequent CHF triggering by rapid spreading on a boiling surface. The surface temperature initiating the formation of the irreversible dry spot was measured to 134 °C, which is far lower than the Leidenfrost temperature and the maximum liquid-contact temperature reported by other studies. To provide qualitative explanations of the CHF triggering mechanism related to the irreversible dry spot, a conceptual boiling curve was presented. It can consider the hydrodynamic and thermal effects postulated on the boiling surface in the time-varying manner of dry spots and their re-wetting.

1. Introduction

The nucleate boiling heat transfer at a high heat flux is the most effective mechanism to remove a large amount of thermal energy from a hot surface owing to the high heat transfer coefficient (O[h] ~ 10^3–10^5 W/m^2 K), whereby a relatively low surface temperature is maintained. Thus, the phenomenon has been applied to several engineering and industrial fields requiring the removal of a high heat flux, such as power plants, electronic chip cooling, and marine ship power generation. However, the boiling crisis, called the critical heat flux (CHF), which limits the nucleate boiling heat transfer, is a crucial phenomenon that threatens the safety of a boiling surface owing to burnout. In the boiling process with surface heat flux control, as the heat flux increases, the abrupt transition from nucleate boiling, in which several vapour bubbles repeat the cycle of generation, growth, coalescence, and departure from a surface, to the film-boiling regime, in which the entire surface is covered with a large vapour film, gives rise to a drastic surface temperature increment. And, in the temperature controlled boiling system, the abrupt temperature rising would not occurred. But, beyond a particular temperature, in which the surface heat flux has a maximum value, the transition from nucleate boiling to film boiling appears, and then the surface heat flux value decreases. And, after the surface temperature reaches to Leidenfrost temperature, in which the surface heat flux has a minimum value, the complete film boiling region can be shown.

In the past 50 years, several theoretical models and perspectives regarding experimental measurements have been presented for explaining and qualifying the CHF triggering mechanism. The first theoretical explanation for CHF triggering was presented by Kutateladze [1] and Zuber [2] in their hydrodynamic theory based on the Kelvin–Helmholtz instability. The theory postulated that the CHF occurs when the surface-fluid interface is broken as a result of the velocity difference between the ascending vapour column and the liquid descending because of gravity. On the basis of this hydrodynamic origin, several researchers [3–6] have presented the CHF triggering model with appropriate modifications. Haramura and Katto [3] presented, according to observations of the macrolayer by Gaertner [7], a theoretical CHF model hypothesising

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* Corresponding author.
E-mail address: hdkims@khu.ac.kr (H. Kim).

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the existence of a mushroom bubble generated by the merging of single bubbles and the macrolayer (combination of vapour stems and liquid film) on the heating surface near the CHF condition. They postulated that the CHF is triggered when the liquid within the macrolayer is completely evapourated during the hovering of the mushroom bubble. However, these CHF models based on a purely hydrodynamic origin have been consistently challenged by several experimental observations and modelling studies that considered the formation of dry spots on a heating surface and their behaviours at a high heat flux and wall superheat conditions (thermo-hydrodynamic origin) as the most essential parameters triggering the CHF.

A relationship between the CHF and the local existence of dry spots on a heating surface was first reported by Kirby and Westwater [8]. They showed that the CHF occurs at one of the dry spots before the complete evaporation of the liquid in the macrolayer. Prior to this conjecture, Semeria and Martinet [9] presented the mathematical formulations governing the thermal conditions for the expansion and resorption conditions of a dry spot (called a calefaction spot), along with experimental measurements. To derive the governing equations and boundary conditions, they adopted the thermal energy balance equation considering the one-dimensional conduction inside the heater material and the convection from the surface to the fluid region. Kovalev [10] and Van Ouwerkerk [11] used a similar approach to describe the stability of the dry spot. To our knowledge, the first direct visual observation of the dry spot distribution and dynamics was conducted by Van Ouwerkerk [11]. He utilised the total reflection technique for the direct detection of dry spots under a high heat flux nucleate boiling condition. Through clear observations of the dry spot on the heater surface and theoretical considerations, an explicit equation for determining the critical radius of a dry spot at a given heat flux was developed. He conjectured that a dry spot smaller than the critical radius is unstable and disappears, and the larger one is stable and irreversibly expanded. Moreover, he considered the thermal properties of the heating material, e.g. $\sqrt{k_s \rho_s c_s}$, where k_s, ρ_s, and c_s are the thermal conductivity, density, and specific heat, respectively, as key parameters influencing the CHF. Nishio et al. [12,13] used the total reflection technique on a transparent electro-conductive film heater. Through visual observations of the dry spots, they measured the ratio of the liquid contact areas to the dry areas and the contact line length density. As a primary result, they showed that the dependence of the contact line length density on the wall superheat values is very similar to that of the heat flux in the normalised boiling curve. Chung and No [14] investigated the dynamic behaviour of dry spots with high speed sequential images obtained using the total reflection technique. Remarkably, they reported the agglomeration of nucleating bubbles in the local wetted region around the large vapour dry patch near CHF condition, and the rewetting of liquid in the dry region was precluded by the phenomenon.

Dinh et al. [15] presented a phenomenological CHF mechanism. In their study, the CHF phenomenon is governed by the interactions between molecular-wicking-controlled contact line motion and liquid supply to opening dry spots. Recently, through careful observations of the boiling structures according to synchronised views of the side and bottom (using the total reflection technique), Chu [16] and Chu et al. [17,18] suggested a CHF triggering mechanism by focusing on the dynamics of the irreversible dry patch. They reported the existence of a small residual dry area immediately after the departure of a large coalesced bubble and conjectured that the residual dry area expands because of the vigorous bubble nucleation around that area and that the CHF is subsequently triggered by the irreversible growth of the dry spot.

Although the direct observation results of the dry spot distribution and dynamics obtained by using the total reflection technique with the optically transparent heater yielded successful explanations and well-established physical insights regarding the CHF triggering, the local temperature distribution and behaviour at the dry spot were not considered or measured. The local temperature of the dry surface may be a crucial parameter for investigating the thermal structures in the vicinity of the dry spots, the consequent liquid rewetting capability at the spots, and the stability of the nucleate boiling heat transfer. Kenning [19] measured the temperature patterns on the backside of a thin stainless-steel heating plate during the pool boiling of water using liquid crystal thermometry. However, the measurement technique had a narrow measurable temperature range, and experimental observations of the dry spot distribution and dynamics were not reported. Theofanous et al. [20] first used high-speed infrared (IR) thermometry for measuring the local wall temperatures in a horizontal pool boiling condition. In their experimental setup, a Ti-glass heater was used, and the local surface temperature at the top of the thin-film heater was measured. However, the dry spots were indirectly detected using the surface temperature data. Recently, Geradi [21] investigated the local surface temperature behaviour on the pool boiling tests of water by high-speed IR thermography using an indium tin oxide (ITO)-sapphire heater.

According to the aforementioned literatures, the boiling heat transfer is an intimately coupled phenomenon postulated by the liquid–vapour hydrodynamics and liquid–solid thermal transport characteristics related to the dry spot behaviour (Fig. 1). Therefore, to understand the exact physical phenomena, both the hydrodynamic and thermal effects, as well as simultaneous measurements of them, are essential. From this perspective, the existing studies have deficiencies. Sadasivan et al. [22] suggested high-resolution and high-frequency measurements of the heater surface temperature, along with experiments for elucidating the effects of the liquid supply to the heater surface on the transient variation of the heater surface temperature. In the review article, they concluded that experiments designed to conduct transient local point measurements of the surface temperature and near-surface vapour content are helpful for clarifying the characteristics of the macrolayer.

Most recently, Kim and Buongiorno developed an infrared thermometry technique [23,24] called Detection of Phase by IR Thermometry (DEPIcT) that may enable simultaneous measurements of the hydrodynamics and thermal behaviour on a boiling surface. Their studies confirmed that the careful calibration of the infrared radiation according to the dry spots with a reference temperature yields quantitative data regarding the surface temperature and phase distribution, thereby providing physical insights into the nucleate boiling phenomena.

In this study, we simultaneously observed the vapour–liquid phase distributions and the surface temperature evolution of the dry spots formed in the nucleate boiling state at a high heat flux. The CHF triggering phenomena were minutely analysed using high-speed sequential infrared images, whereby the vapour–liquid phase distributions (dry spot formations and dynamics) were quantified, as well as sequential local surface temperature data were obtained for the region beneath the dry spots. The experimental measurement techniques and high-resolution data of the phase distribution and local surface temperature in the present study could be considered as an advanced accomplishment compared to the previous studies [23,24].

In Section 2, the methods for measuring the dry spot areas and local temperature using the infrared thermometry technique are explained. The experimental setup is briefly described in Section 3. In Section 4, the observations and analysis results for the dry spot