International Journal of Heat and Mass Transfer 128 (2019) 229–238

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Observation of the mechanism triggering critical heat flux in pool boiling of saturated water under atmospheric pressure

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A R T I C L E I N F O

Article history:
Received 19 March 2018
Received in revised form 18 August 2018
Accepted 29 August 2018

Keywords:
Bubble nucleation
Critical heat flux
Dry patch
Pool boiling
Triple contact line

A B S T R A C T

We observed the dynamics of dry patches underneath massive bubbles during the pool boiling of saturated water under atmospheric pressure, and measured the associated temperature distribution. We synchronized the observations both spatially and temporally using high-speed total reflection and infrared thermometry techniques. The observations presented in this paper provide evidence that the critical heat flux phenomenon is triggered during the rewetting of large dry patches with periphery temperatures that are much lower than minimum film boiling temperature, so-called Leidenfrost point. As the liquid meniscus advanced toward the dry patch, numerous secondary bubbles nucleated and impeded the flow of liquid toward the dry patch. This prevented the liquid from rewetting the dry patch. The key physical mechanism for triggering CHF is initiated when the line density of the secondary bubbles nucleating at the periphery of a shrinking dry patch underneath a departing mushroom bubble exceeds a critical value. These bubbles completely block the liquid inflow into the dry patch and prevent rewetting, eventually causing the dry patch to expand irreversibly. We used our experimental data to determine an empirical value of the critical line nucleation site density.

1. Introduction

Nucleate boiling heat transfer is used widely in industrial applications with high heat fluxes, such as in steam generators in nuclear and fossil power plants, the cooling of plasma-facing components in fusion reactors, and microchannel heat exchangers in electronic chips [1–3]. However, the cooling performance of nucleate boiling is limited by the critical heat flux (CHF), which causes the heat transfer coefficient to deteriorate suddenly, and eventually causes the system to fail. Predicting the thermal-hydraulic design limit, namely the CHF conditions, remains one of the most important challenges for maintaining system safety in high heat flux boiling applications. We can improve our predictions of when CHF will occur by gaining a detailed understanding of the mechanisms that trigger CHF.

Several theoretical models have been proposed to explain the mechanisms that trigger CHF. However, there are significant discrepancies between the physical picture of the two-phase flow behavior during CHF and the criteria used to identify CHF. Of the current theoretical models, the hydrodynamic, liquid macrolayer, and dry spot models are considered to best represent CHF. The hydrodynamic instability model was suggested by Kutateladze [4] and Zuber [5]. They hypothesized that CHF is triggered when the velocity difference between the vapor and liquid phases at the interface is sufficiently larger than the critical value to cause disruption to the continuous flow of vapor from the surface of the heater. Meanwhile, the liquid macrolayer model, proposed by Haramura and Katto [6], is based on observations of thin liquid layers trapped by several vapor stems underneath a mushroom bubble [7]. They assumed that CHF occurs upon the evaporation of the macrolayer after the departure of a mushroom bubble. The dry spot model, proposed by Ha and No [8,9], is based on the hypothesis that the supply of liquid into the microlayer underneath a central bubble becomes restricted when the number of surrounding bubbles exceeds some critical value. The increase in the number of such central bubbles, which have dry spots underneath them, prevents effective heat removal and eventually causes CHF. Even though the models give reasonable predictions of the CHF values, it is difficult to explain the experimental findings regarding the formation of dry patches on heated surfaces and their role in CHF, such as those of Van Ouwerkerk [10], Nishio et al. [11], and Chu et al. [12,13], in terms of the models based on theoretical frameworks. Additionally, these models do not take into account the effects of the thermal behavior of dry patches on CHF, even though

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.128
0017-9310/

there is evidence that CHF is closely associated with the thermal behavior of dry patches on heated walls [10,14–19].

Recently, Choi et al. [20] developed a model of dry patches based on the direct observation that dry patches play an important role in CHF [12,13], extending the dry spot model suggested by Ha and No [9,10]. They assumed that CHF is initiated by the onset of an unquenchable dry patch that satisfies both hydraulic and thermal criteria: the hydraulic criterion requires a critical number of dry spots to cause the formation of a dry patch; and the thermal criterion states that the peripheral temperature of the dry patch must be above the Leidenfrost temperature. However, the thermal criterion of this dry patch model contradicts the experimental observation that the surface temperature is far lower than the Leidenfrost temperature upon the initiation of CHF [16–19]. Therefore, this CHF model can be improved further. Experimental observations provide useful insights for understanding and modeling the CHF phenomenon. Detailed observations of the dynamics of dry patches and their thermal behavior on boiling surfaces will contribute greatly to improving our understanding of CHF.

Various high-speed and high-resolution techniques for visualizing boiling surfaces have been used to observe the CHF phenomenon, including total reflection and infrared thermometry techniques, as well as side visualization. The total reflection technique permits the detection of dry areas underneath vapor bubbles on a transparent boiling surface. Nishio and Tanaka [21] observed liquid-solid contact patterns in high heat-flux boiling on a transparent heating surface using the total reflection technique. They proposed the contact-line-length density as a new measure of the contribution of liquid-solid contact to high heat-flux boiling heat transfer. Chung and No [22] observed the dynamic behaviors of both bubbles and dry spots on boiling surfaces using the total reflection technique, and made direct observations from the bottom of the surface. They observed that the dry area occupied more than 70% of the entire heated surface at CHF, and reported a strong relationship between limited bubble nucleation at the wetted area and CHF. Recently, Chu et al. [13,14] suggested a potential CHF triggering mechanism based on their observations of the formation of residual dry patches using the total reflection technique. They observed that the active coalescence of newly generated bubbles with existing bubbles causes a residual dry patch to arise, and prevents the complete rewetting of the dry patch, thus leading to CHF.

Other researchers have used high-speed infrared cameras to measure the local surface temperatures of dry patches. These studies were conducted due to the importance of the effects of the thermal behavior on the growth of dry spots/patches. Theofanous et al. [16,17] measured the local temperature on the surface using a high-speed infrared thermometry technique. They observed the growth of a dry spot prior to and during the burnout of the heater. Later, Gerardi [18] studied the behavior of hot spots on the surface using infrared thermometry. Reversible and irreversible hot spots were distinguished according to whether the hot spot was rewetted with liquid, and CHF was considered to occur when an irreversible hot spot was initiated. Kim et al. [19] observed the temperature evolution and dynamics of dry spots using the DEPIcT technique. They observed an irreversible dry spot on the heating surface under CHF conditions. The surface temperature inside the dry spot was 135 °C at the time of its initiation.

Although the previous visualization studies have provided important insights into the mechanisms that trigger CHF, there are still deficiencies in the mechanistic prediction model of CHF. This is due to the lack of vital information about the effects of the coupling between the hydrodynamics and heat transfer during the rewetting of the dry patch. In this study, we simultaneously observed the hydrodynamic and thermal behavior of dry patches on heated surfaces so that we could comprehensively investigate the mechanisms that trigger CHF during pool boiling. We achieved this using an integrated, fully spatially and temporally synchronized, high-speed total reflection and infrared thermometry technique. We then investigated the effects of the interactions between the hydrodynamics and heat transfer processes associated with the triggering of the CHF phenomenon.

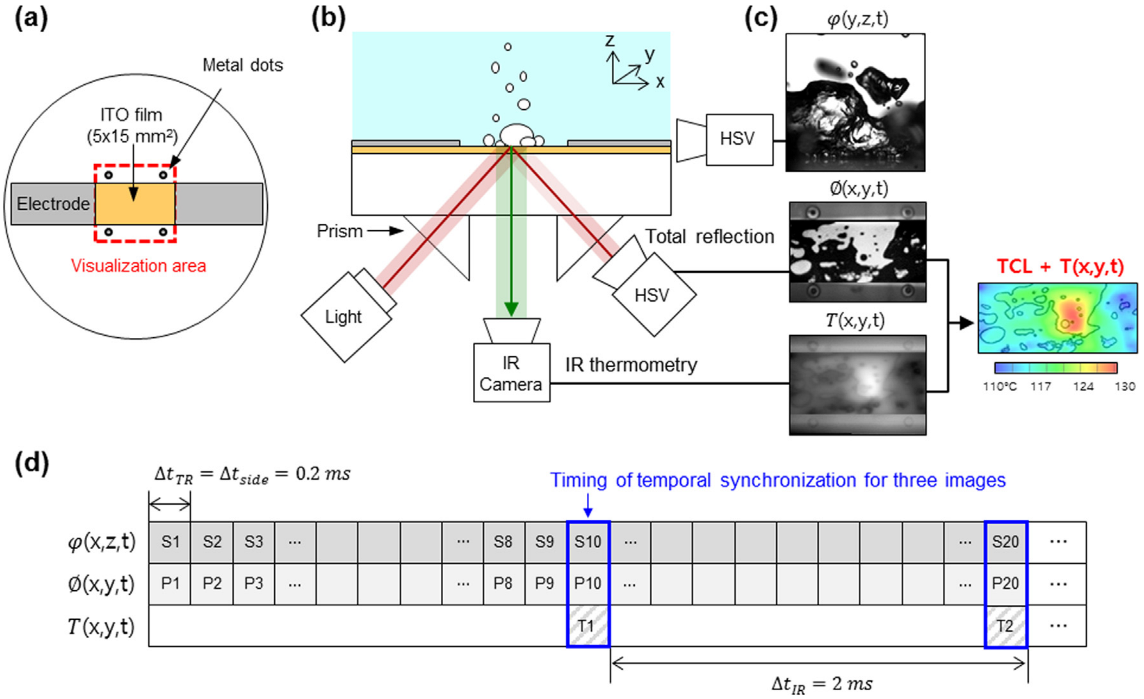

Fig. 1. Experimental method to simultaneously measure the dynamics and thermal behavior of dry patches on a boiling surface. (a) Schematic diagram of a test sample. (b) Schematic diagram of the setup for optical measurements (c) Images of bubble structures, the liquid-vapor phase, and wall temperature distributions. (d) Configuration of the apparatus used to synchronize the measurements temporally.