



The suppression effect of easy-to-activate nucleation sites on the critical heat flux in pool boiling

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ABSTRACT

We report experimental studies of the role of easy-to-activate nucleation sites in pool boiling on hybrid hydrophobic-hydrophilic surfaces. Microstructured surfaces with controlled wettability and nucleation sites are designed and fabricated to investigate their individual and collective effects on the boiling heat transfer performance. Our results reveal that excellent critical heat flux (CHF) up to 231.5 W/cm^2 is attainable only when the surface has good wettability but is free of easy-to-activate nucleation sites. However, with the presence of easy-to-activate nucleation sites on the boiling surface, only limited CHF's can be achieved irrespective of the surface wettability, suggesting a suppression effect of nucleation sites on the CHF. Based on the previous experimental observation of the dynamic network-like wetting pattern at high heat fluxes, a wetting-deterioration mechanism is proposed to explain the suppression effect of easy-to-activate nucleation sites on the CHF. Easy-to-activate nucleation sites continuously generate bubbles that pose a large flow resistance for the liquid to wet the hot surface and thus lead to early dry-out.

1. Introduction

Compared to the traditional single-phase convection, heat transfer efficiency of boiling is up to two orders of magnitude higher [1], not only because of the vigorous two-phase disturbance but also the large latent heat dissipated through evaporation. Owing to its excellent heat transfer performance, boiling has been widely applied in multiple kinds of industries including nuclear power generation, chemical processing, and water desalination [2,3]. For nucleate boiling, critical heat flux (CHF) and heat transfer coefficient (HTC) are two important parameters to characterize the heat transfer capability of a boiling surface. CHF refers to the maximum heat flux allowed for nucleate boiling on a heated surface, above which the surface will be overheated and severely damaged. High HTC enables a large heat flux at a specified superheat (temperature difference between a heated solid surface and a working fluid).

In the past few decades, various factors have been examined to understand the mechanism causing the CHF, for example, fluid hydrodynamics [4,5], surface wettability [6–11], wickability [12,13] or capillarity [14,15], and nucleation sites [16–19]. To date, many correlations and models have been proposed for the CHF [4,20]. The most well-known model, proposed by Zuber [4], attributes the occurrence of

the CHF to the Kelvin-Helmholtz instability of regularly-spaced vapor columns. Although this model shows good agreement with some experimental results, it has been challenged by recent experiments on micro/nanostructured surfaces [12–15,21–27]. In recent years, significant advances have been achieved on the enhancement of the CHF beyond the hydrodynamic limit by using various microstructures and nanostructures on the boiling surfaces [12–15,21–27]. Several near-field mechanisms are proposed to account for the effects of fluid flow and heat transfer near the heated surface on the CHF [6,28]. The CHF enhancement on microstructured/nanostructured surfaces has also been attributed to other factors including large capillary forces [14], increase of nucleation site density [15,16], and enhanced liquid-solid contact area [15,23,26]. On the other hand, a fractal analysis approach [29,30] has been adopted to analyze the distribution of active nucleation sites on a boiling surface and a fractal model was developed for the CHF. Despite several decades of theoretical and experimental studies, no consensus has been reached on the exact mechanism that leads to the CHF phenomena.

Although the CHF mechanism is not well understood yet, it has been commonly believed that surfaces with good capillarity and wettability can obtain excellent CHF's and hydrophobic surfaces are advantageous to realize high CHF's and high HTC's. Is it possible to achieve high CHF and high HTC

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simultaneously on one boiling surface? Several pioneering works have explored such possibility with the strategy of patterning hydrophobic regions on hydrophilic or superhydrophilic surfaces [16–19]. Betz et al. patterned Teflon patches on HF-treated SiO₂ surfaces; and they reported a CHF of 190 W/cm² and a HTC of 7 W/cm²-K, corresponding to 65% and 75% enhancement compared to the counterparts of the plain HF-treated SiO₂ surfaces [16]. However, their more recent work showed a conflicting trend that the superhydrophilic surface with superhydrophobic patches demonstrated a CHF lower than the homogeneous superhydrophilic surface [17]. Jo et al. studied the boiling behavior of plain Si/SiO₂ surfaces with Teflon dots as easy-to-activate nucleation sites [18,19]. They reported that the CHFs of the hybrid surfaces were similar to those of plain Si/SiO₂ surfaces, while HTCs were enhanced by up to 70%. From these studies, it is hard to draw a conclusion whether the CHF and HTC can be simultaneously enhanced on one surface.

To address the above issue, we have designed and fabricated a series of microstructured surfaces with controlled wettability and nucleation sites in this work. Systematic boiling experiments were conducted to explore whether high CHF and high HTC can be simultaneously achieved on the same boiling surface.

2. Design and fabrication of microstructured surfaces

For a systematic comparison, a total of eight types of samples with different surface coatings and cavity sizes have been designed and fabricated. The schematics of different types of samples are shown in Fig. S1 (supporting information). Si-type samples (Si70 and Si110) with the bare Si microstructures are fabricated to serve as the reference in this study. O-type samples (O70 and O110) with the whole surface coated with SiO₂ are designed to have a good wettability. T-type samples (T70 and T110) with Teflon-coated cavities and Si microstructures are designed to have easy-to-activate nucleation sites, while TO-type samples (TO70 and TO110) with Teflon-coated cavities and the SiO₂ coating on the remaining surface are designed to have both good wettability and easy-to-activate nucleation sites. Two cavity sizes are considered for each type of samples. The number in the sample label, for example, Si70, represents the cavity size.

The surface structure of the boiling samples is shown in Fig. 1. All the samples have a size of 1 cm × 1 cm (Fig. 1a). As shown in Fig. 1b, the sample surface has three main features: ① micropillar arrays, ② central cavity, and ③ water channel. Micropillar arrays are designed to be the capillary structure to supply the water from large water channels to the central cavity. In general, small dimensions are preferred for micropillars and the spacing between micropillars. A recent work on micro- and nano-textured Si surfaces showed that the CHF could be maximized at an optimal micropillar spacing of ~10 μm [14]. Therefore, we chose 10 μm for both the side length of square micropillars and the spacing between two neighboring micropillars in our design. The height of micropillars is 50 μm. In order to study the effect of nucleation sites on the boiling heat transfer performance, central cavities for T-type and TO-type samples are designed to be easy-to-activate nucleation sites. Teflon is coated on the surface of the cavity to enhance the effectiveness of those cavities as nucleation sites, as shown in Fig. 1d. Central cavities for Si-type and O-type samples are designed to be ineffective nucleation sites for comparison. The cavity sizes are then selected to be effective nucleation sites for Teflon-coated cavities (T-type or TO-type) but ineffective nucleation sites for Si or SiO₂ cavities (Si-type or O-type). Fig. S2 shows the estimated ranges of the cavity size to activate a bubble on Teflon, Si, and SiO₂ surfaces. The cavity sizes of 70 μm and 110 μm satisfy the requirement and are considered in our design to study the effect of the cavity size on the boiling performance. The side length of square Teflon patches is designed to be slightly smaller than the cavity size: 50 μm for the 70 μm cavity and 90 μm for the 110 μm cavity. The total area of the Teflon-coated regions only accounts for 1.47% for the samples with the cavity size of 110 μm and 0.43% for the samples with the cavity size of 70 μm. As seen in Fig. 1c

and d, each square unit of micropillar arrays is designed to have a lateral dimension of 290 μm. The water channels between square units of micropillar arrays are designed to have a small flow resistance to supply water to the central cavity through micropillar arrays. Thus, a large dimension is preferred. We have selected 100 μm for the width of water channels.

The samples were fabricated on Si substrates by standard micro-fabrication techniques. As an example, schematics of the fabrication process for TO-type samples are shown in Fig. 2. A triple-layer of metals (90 nm Cr/200 nm Ni/300 nm Cu) was first sputtered at the backside of the Si substrate for bonding with the boiling setup. Then, central cavities were patterned by photolithography and etched down to 50 μm by deep reactive ion etching (DRIE). Next, 100 nm thick Teflon was coated on the surface through atmospheric pressure chemical vapor deposition (APCVD). After removing photoresist, micropillar arrays and water channels were patterned and etched down to 50 μm by photolithography and DRIE. Then, SiO₂ was sputtered on the surface of micropillar arrays and water channels to enhance the surface wettability. It is worth noting that sputtering was performed twice at two inclined angles to ensure the coverage of side walls of micropillar arrays. Each time, 100 nm thick SiO₂ was deposited. The fabrication process was completed after removing the photoresist. T-type samples were fabricated by following a similar process except skipping step h in Fig. 2. For O-type and Si-type samples, central cavities, micropillar arrays, and water channels were defined and etched simultaneously by photolithography and DRIE. Then, for O-type samples, SiO₂ was sputtered twice at two inclined angles to enhance the surface wettability.

3. Boiling experimental setup and sample testing device

Fig. 3a shows the schematic of our pool boiling experimental setup. A testing device was designed and manufactured to heat up the sample during the boiling process and meanwhile measure the boiling curves. Before the experiment, the sample was bonded onto the Cu block (embedded in the testing device) by using the soldering tin. The triple-layer (Cr/Ni/Cu) metallization scheme [31,32] we adopted can ensure good bonding quality between the sample and the Cu block during the boiling experiment. The failure temperature of the soldering tin is 183 °C, which is well above the measurement temperature range of our samples. Epoxy was applied at the edge of the sample to reduce the heat loss during the boiling experiment. Then, the testing device was placed in a quartz chamber. The deionized (DI) water was filled into the chamber and heated up to the saturation temperature (~100 °C) by using a hotplate. Degassing was carried out for 30 min before the experiment. A high-speed camera is placed at the side of the chamber to record the boiling process and a high-intensity LED light source is used to illuminate the view field.

Fig. 3b shows the parts of the testing device. The Cu block is embedded in heavy Teflon blocks for thermal insulation purpose. The upper part of the Cu block has a square cross section of 1 cm × 1 cm, the same as the size of our boiling samples. Six thermocouples were installed along the vertical centerline of the Cu block to measure the temperatures. It is worth noting that there is a through hole on the top surface of the Cu block in our experimental setup. The top thermocouple is in direct contact with the backside of the Si substrate during the boiling experiments. The distances of other five thermocouples from the top surface of the Cu block are 3 mm, 7 mm, 11 mm, 15 mm, and 19 mm, respectively. A cartridge heater is inserted into the lower part of the Cu block for heating up the sample as shown in Fig. 3b. All the gaps of the testing device are sealed with the waterproof silica. Thermocouples are connected to a data logger (Agilent 34970A) to record temperature readings. Typical temperature distribution along the Cu block in a pool boiling experiment is shown in Fig. S3 (supporting information). The surface superheat can be calculated from the temperature reading of the top thermocouple, the saturation temperature of water, and the estimated temperature drop across the Si substrate. The

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