



Pool boiling heat transfer enhancement with electrowetting

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ARTICLE INFO

Article history:

Received 27 September 2017

Received in revised form 5 December 2017

Accepted 6 December 2017

Keywords:

Pool boiling
Heat transfer
Electrowetting
Boiling heat transfer coefficient
Critical heat flux
Film boiling

ABSTRACT

Electrowetting (EW) has drawn significant research interests in droplet-based microfluidics, and most applications focus on electronic displays, lab-on-a-chip devices and electro-optical switches, etc. This paper presents a new application of EW in enhancing pool boiling heat transfer. The working approach capitalizes on the complimentary roles of hydrophobicity and hydrophilicity played in boiling and takes advantage of the ability of EW to alter the surface wettability dynamically and reversely. In this work, the effects of alternating current EW (ACEW) on the heat transfer characteristics of various boiling regimes, including the onset of nucleate boiling (ONB), fully developed nucleate boiling, and film boiling at critical heat flux (CHF) conditions, are investigated. A synchronized high-speed optical imaging and infrared (IR) thermography approach is taken to obtain simultaneous measurements of the bubble dynamics and the wall temperature and heat flux distributions on the boiling surface. Based on the experimental data, boiling curves are constructed and the boiling heat transfer coefficients (BHTCs) are computed. Comparisons with the boiling characteristics of the baseline surface without ACEW demonstrate the efficacy of ACEW in enhancing the performance of pool boiling heat transfer. Some insights are also offered to understand the physics of the ACEW-enhanced boiling behaviors.

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1. Introduction

As an effective means of transferring large amount of thermal energy, pool boiling has been employed in various industries involving energy conversion and power generation [1]. The boiling performance is generally characterized by two parameters, the boiling heat transfer coefficient (BHTC) and the critical heat flux (CHF). The BHTC represents the heat removal rate per unit temperature rise in the heated surface, whereas the CHF marks the upper limit of nucleate boiling, beyond which the boiling surface is blanketed with an insulating vapor film and catastrophic burnout may occur. Accordingly, the primary goals of boiling heat transfer enhancement have been to maximize the BHTC and to increase the CHF [2]. Current prevailing approaches are based on chemically or topographically modifying the boiling surface, including surface roughening [3–7], surface coating [8–19], and fabricating micro/nanoengineered surface structures [20–33], etc. One key premise of these techniques is that the surface wettability can be tailored to affect various aspects of nucleate boiling, such as bubble nucleation [34–38], bubble dynamics [39–44], and CHF [45–49].

Recently, it was realized that, instead of tuning the wettability over the entire surface, introducing localized wetting heterogeneity appears to be a more effective way to augment the boiling performance. This rationale was inspired by the dual role of surface wettability played in boiling, i.e., hydrophobic surface promotes bubble nucleation and increases BHTC, whereas hydrophilic surface is beneficial to CHF enhancement [50,51]. Consequently, biphilic surfaces with alternating hydrophobic and hydrophilic regions have been manufactured by patterning a hydrophilic surface with hydrophobic materials [41,51–60] or functionalized nanostructures [61–65]. Significant improvements in both BHTC and CHF were observed on the biphilic composite surfaces, partially due to the increased active nucleation site density, higher bubble growth rate and faster bubble departure frequency as well as the less likelihood of film boiling. Thus, it is concluded that a boiling enhancement surface should consist of a continuous hydrophilic background with distributed hydrophobic spots in order to yield optimized boiling heat transfer characteristics.

While the biphilic surfaces are promising, the main disadvantage is their static and passive nature. Once fabricated, these surface structures and their functionality can no longer be altered. On the other hand, the heat transfer conditions encountered in practical boiling systems, e.g., the boiler in a steam power plant, often fluctuate over time, which may be due to the load-following operations to

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cope with fluctuating electric demands or the irregularities in the working environment. Under the dynamic conditions, the ability to actively control the boiling characteristics is highly desirable: a hydrophobic surface is maintained at low heat fluxes for the sake of good BHTC, whereas it can be tuned to hydrophilic at high heat fluxes to enhance CHF.

To date, there have been very few studies addressing active, on-demand surface wettability control for boiling heat transfer enhancement. In one approach, ultraviolet (UV)-visible light was employed to induce the hydrophilic-hydrophobic transition on boiling surfaces coated with photosensitive materials, such as TiO₂ [66,67], carbon nanotubes (CNTs) [68] or organic polymers [69]. Nucleate boiling heat transfer is drastically improved on these light-irradiated surfaces. However, the light irradiation time required to achieve the wettability transition, ranging from 5 min to 50 h, is overly long as compared to a typical boiling ebullition cycle of one to a few seconds. In another study [70], bubble nucleation was manipulated by applying an electric potential to control the adsorption and desorption of charged surfactants on the boiling surface. Adsorption of negatively charged surfactant (sodium dodecyl sulfate) under a positive potential exposes the hydrophobic components of the surfactant to the liquid and renders the surface hydrophobic, thereby promoting nucleation. When the potential is reversed, the surfactant molecules are repelled from the surface, which increases the surface wettability and suppresses nucleation. By combining with individually addressable electrodes, both temporal and spatial control of surfactant boiling was successfully demonstrated.

In this work, an alternative approach for active boiling enhancement, which capitalizes on the ability of electrowetting (EW) to rapidly modulate the surface wettability in a reverse and robust manner, is presented. With this approach, an inherently hydrophobic boiling surface operates at low-to-moderate heat fluxes, so that the onset of nucleate boiling (ONB) commences spontaneously and excellent BHTC can be obtained. When bubble coalescence intensifies at high heat fluxes, EW effect can be actuated to change the surface to a hydrophilic one within a fraction of a second, thereby keeping the surface rewettable to delay CHF. Furthermore, since alternating current-driven EW (ACEW) is used in the present study, time-harmonic shape oscillations are stimulated at the liquid-vapor interface [71], which can be harnessed to yield favorable bubble dynamics and induce interfacial instability suppress the occurrence of film boiling. To study the ACEW-enhancement of pool boiling heat transfer, experiments are conducted over a wide range of boiling conditions, from ONB, fully developed nucleate boiling to film boiling at CHF, on a hydrophobic surface (as the baseline) and an ACEW-enhanced surface, respectively. A synchronized high-speed optical imaging and IR thermography method is utilized to simultaneously acquire the bubble dynamics and the spatiotemporally resolved wall temperature and heat flux distributions on the boiling surface. The rest of the paper is organized as follows. First, the background of EW is briefly reviewed. Then, the experimental apparatus and the measurement methods are described. Subsequently, the experimental results of pool boiling heat transfer on the two surfaces are presented and compared, and some physical insights are offered to understand the effects of ACEW on various fundamental aspects of pool boiling.

2. Electrowetting

Surface wettability can be altered dynamically by a myriad of external means. For example, light radiation, temperature, magnetic field, electric field and selected solvents have been used to induce the hydrophobic-hydrophilic transition [72–76]. Among them, electrowetting is particularly attractive for its fast response,

excellent reversibility, ultralow power consumption and superb robustness [77,78]. As shown in Fig. 1, a sessile liquid drop resides on a hydrophobic surface with an underneath electrode. The initial contact angle is the intrinsic contact angle, θ_0 . When a voltage signal is applied, the contact angle decreases from θ_0 to a smaller value, θ_a , i.e., the apparent contact angle. The spontaneous spreading of the drop indicates the wettability transition (Fig. 1(c)). The EW-induced contact angle variation can be described by the Lippmann-Young equation

$$\cos \theta_a = \cos \theta_0 + \frac{\epsilon_0 \epsilon_d}{2\sigma_{lv}d} V^2 \quad (1)$$

where V is the applied voltage, ϵ_0 the permittivity of the vacuum, ϵ_d the dielectric constant, d the thickness of the dielectric layer, and σ_{lv} the interfacial tension of the liquid-vapor interface. For a water drop resting on a Teflon-coated surface with silicon dioxide as the dielectric layer ($\theta_0 = 120^\circ$, $\sigma_{lv} = 0.072$ N/m, $\epsilon_d = 3.9$, and $d = 500$ nm), Fig. 2 illustrates that the contact angle decreases from $\theta_0 = 120^\circ$ to $\theta_a = 85^\circ$ when V is increased from 0 V to 35 V. It is noted that θ_a reaches the minimum (80°) at $V \approx 37.5$ V and remains constant irrespective of further increase in V , a phenomenon called the “contact angle saturation”. Nonetheless, Fig. 2 attests that with a moderate voltage signal, the surface wettability can be tuned by EW effectively between the hydrophobic and hydrophilic states. Considering the intimate connection between surface wettability and boiling, Brawlower [79] attempted to enhance pool boiling with direct current (DC) electrowetting, however, his experimental data showed that, on the contrary, boiling heat transfer is severely deteriorated.

Fortunately, EW can also be induced by alternating current (AC) voltage signals [80,81]. In ACEW operation of a liquid drop, a periodic electrical force is exerted on the contact line, which leads to not only the contact line motion but also capillary wave patterns at the liquid-vapor interface [82,83]. When ACEW is acting on a vapor bubble, similar interfacial oscillations can be stimulated to induce strong streaming flow around the bubble [71,84]. Hence, it is reasonable to anticipate the streaming flow will favorably reinforce the microconvection as well as the free convection in boiling heat transfer. More importantly, as will be discussed later, ACEW-induced interfacial oscillations have a profound impact on the bubble ebullition process and the instability of film boiling. Consequently, ACEW has the potential to be exploited as a powerful tool to improve BHTC and enhance CHF.

3. Experimental methods

3.1. Electrowetting-boiling test device

The EW-boiling test piece is shown in Fig. 3. A 385- μm -thick 3” silicon wafer (Silicon Quest) is used as the substrate, which also functions as the actuating electrode for EW due to the reasonable electrical conductivity of silicon (1.56×10^{-3} S/m at 20 °C). The wafer has a 500-nm-thick native layer of silicon oxide (SiO₂) thermally grown on both sides. The SiO₂ layer is employed as the dielectric material as SiO₂ has a dielectric constant higher than most fluoropolymers that are commonly used in EW studies. A thin layer (70 nm) of Teflon (AF2400, Dupont) is spin-coated on the wafer to generate the hydrophobicity. To improve the affiliation of Teflon to SiO₂, a silane-based adhesion promoter (FSM-660-4, Cytonix) is dip-coated on the surface before spin-coating Teflon. On the other side of the silicon wafer, a chromium (Cr) thin-film heater (20 mm long \times 20 mm wide \times 200 nm thick) is fabricated in the center region, as indicated in Fig. 3. Electrical connections to the external circuits are fabricated using copper (Cu). The heater circuit is electrically separated from the EW circuit by the SiO₂ layer.

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