



Influence of microstructure geometry on pool boiling at superhydrophobic surfaces



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ABSTRACT

Periodically patterned superhydrophobic surfaces with rectangular rib and circular post arrays were utilized as heat transfer surfaces in a boiling apparatus with the water pool undergoing saturated pool boiling. The surface microstructures were geometrically defined by cavity fraction (the ratio of projected cavity area to surface area), pitch (the center to center distance between microfeatures), and feature height. Surface heat flux and surface superheat, the difference between the heated surface and the pool saturation temperature, were measured for each surface. Ten different micropatterned surfaces with post or rib geometries were considered with cavity fraction varying from 0.5 to 0.98, pitch varying from 8 to 40 μm , and microfeature height at 4 μm or 15 μm . The surface heat flux was measured across a range of surface superheats spanning 2–38 K. It is demonstrated for the first time that the transition from nucleate boiling to film boiling on rib patterned surfaces depends strongly on the cavity fraction. Increasing the microstructure height from 4 μm to 15 μm modestly increases the transition temperature. Nucleate boiling is more suppressed on post patterned surfaces than on rib patterned surfaces. Further, the rib structured surfaces exhibit a sudden transition from nucleate to film boiling while the post structured surfaces exhibit a gradual transition, with the vapor film growing slowly across the surface. Once stable film boiling is reached, the surface microstructure negligibly influences the heat flux for all surfaces.

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1. Introduction

Pool boiling heat transfer is influenced by many parameters [1,2]. Perhaps the least understood are surface chemistry and micro/nanostructure. The classical approach for considering pool boiling heat transfer is to empirically obtain the relationship between the heat flux at the wall (q_w'') and the surface superheat (ΔT), the difference between the wall temperature and the liquid pool temperature [3,4]. Multiple boiling curves may be obtained for a range of parameters including different substrates, liquids, gravitational acceleration, and ambient pressure. In this paper, the influence of superhydrophobic surface microstructure on pool boiling is characterized.

Superhydrophobic (SHPo) surfaces are realized through the combination of hydrophobic chemistry and micro/nanoscale surface roughness. The development of artificial SHPo surfaces is fairly recent [5] and the influence of these surfaces on pool boiling is an active area of inquiry. This work considers a specific scenario which has not yet been studied: periodically micropatterned SHPo

surfaces of both rib and post geometries. To begin, a brief overview of classical boiling behavior is considered.

Heat flux as a function of the surface superheat has been observed for a wide variety of surface and working fluid combinations [1,6]. This relationship, the “so-called” boiling curve, is illustrated qualitatively for liquid water undergoing saturated pool boiling at atmospheric pressure in Fig. 1, where the general variation in q_w'' as a function of the surface superheat, ΔT , is shown. In general, some portion of the pool may be at a temperature below the liquid saturation temperature. These scenarios are called “sub-cooled pool boiling” and are in contrast to “saturated pool boiling” where the pool is uniformly at the saturation temperature. The scope of this work is limited to saturated pool boiling.

Distinct regimes of physical phenomena are observed in the liquid as ΔT rises. These regimes are labeled in Fig. 1, as well as three important points which are marked A through C. Nucleate boiling begins at $\Delta T \approx 7 \text{ K}$ [2], and a dramatic increase in q_w'' occurs due to phase change and bubble-induced liquid motion. As ΔT increases, the density of nucleation sites becomes sufficiently large that bubble interaction occurs and the bubble release frequency increases until the consecutive bubbles merge into vapor columns. The rate of increase in q_w'' with ΔT decreases as the fraction of the surface area covered by the vapor increases. A local maximum is reached

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Nomenclature

ΔT	surface superheat	w_c	cavity width
d	post diameter	<i>Greek letters</i>	
F_c	cavity fraction	θ	apparent contact angle
h	height	θ_Y	Young's contact angle
q''_w	wall heat flux	<i>Subscripts</i>	
r	roughness ratio, used in Wenzel equation (Eq. (1))	c	critical heat flux point
r_w	roughness ratio of wetted area, used in Cassie equation (Eq. (2))	L	Leidenfrost point
T_s	surface temperature		
T_{sat}	water saturation temperature		
w	pitch		

at the critical heat flux (point B, nominally $\Delta T \approx 30$ K [2]). Two different phenomena may be observed as ΔT increases further, depending on how heat is supplied to the surface. If heat is supplied at constant q''_w , a sudden transition to the film boiling regime is experienced and ΔT increases by 1–2 orders of magnitude [4]. Subsequently, q''_w increases with increasing ΔT and film boiling prevails.

If the surface is maintained at constant temperature, a transition boiling regime will be entered and q''_w will decrease with increasing ΔT until a minimum heat flux is reached [3]. This minimum heat flux and its corresponding surface superheat is known as the Leidenfrost point (point C, $\Delta T \approx 120$ K [2]) and is accompanied by the formation of a stable vapor film. q''_w once again begins to rise as ΔT increases beyond this point, with film boiling existing everywhere on the surface.

Contemporary contributions explaining the influence of micro/nanostructure and surface chemistry on pool boiling are now introduced. Surface-water interaction is typically categorized into four surface types, ranked according to decreasing intermolecular interaction with liquid water: superhydrophilic, hydrophilic, hydrophobic, and superhydrophobic. The static contact angle is used to characterize surfaces in this work. Superhydrophilic surfaces combine hydrophilic chemistry and micro/nanostructure and have contact angles which approach 0° . Hydrophilic surfaces have hydrophilic chemistry and have contact angles spanning 0° to 90° , hydrophobic surfaces have hydrophobic chemistry and have contact angles spanning 90° to 120° , and superhydrophobic surfaces have hydrophobic chemistry and micro/nanostructure with contact angles which span 150° to nearly 180° [7]. Panel (a) of

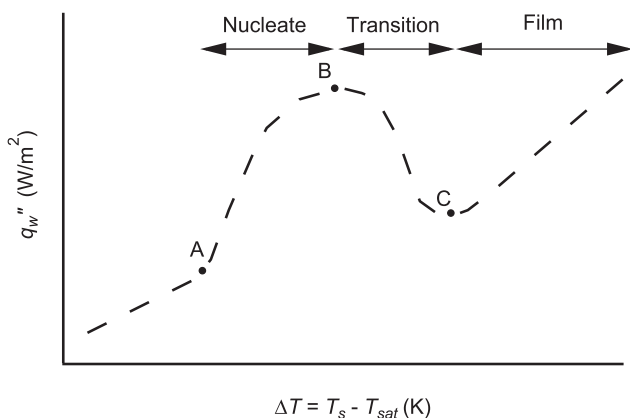


Fig. 1. The qualitative boiling curve for liquid water undergoing pool boiling at atmospheric pressure on a heated classical surface is displayed. Heat flux, q''_w , is plotted as a function of surface superheat, ΔT . Labels A–C indicate the onset of nucleate boiling, the critical heat flux, and the Leidenfrost point. The span of the nucleate, transition, and film boiling regimes are also indicated.

Fig. 2 illustrates schematically water droplets resting on these surfaces, excluding the superhydrophilic case in which a contact angle near 0° would be observed and the surface would exhibit hydrophilic microfeatures.

Due to roughness features on the nanometer to micrometer scale and material which is chemically hydrophobic, water interacts little with a superhydrophobic surface and the liquid cohesion dominates the three phase interaction. As long as the ambient pressure is sufficiently small, the cavities between features do not fill with water and the surface is said to be in the Cassie state (schematically illustrated in panel (b) of **Fig. 2**). This state is prerequisite for many unique SHPo surface properties and is the state considered in this study. The apparent contact angles reported in this work are nominally those which would be obtained with Cassie's equation [8].

Deviations from classical hydrodynamic and thermal transport behavior are observed on superhydrophobic surfaces. Hydrodynamics are altered by the microscopic alternating shear and nearly shear free boundary conditions at the wall. From a macroscopic perspective, it appears as though a slip velocity prevails at the wall. The overall effect is a reduction in friction drag. This has been demonstrated through experiment and analysis in a variety of flows [9–11]. Further, a recent work considering the trajectories of superheated spheres reported trajectory stabilization and drag reduction on superhydrophobic spheres relative to smooth hydrophilic spheres [12]. Reduced adhesion allows water to roll over the surfaces with small resistance washing away contaminants and yielding “self-cleaning” surfaces [13].

The presence of the air-filled cavities also dramatically alters thermal transport. The thermal conductivity of the air and water vapor contained in the cavities is three orders of magnitude less than for the metal substrate. Thus, the water encounters alternating matching temperature and nearly adiabatic boundary conditions. From a macroscopic scale, it appears that a finite jump in temperature occurs at the wall, reducing the wall heat flux [14–16].

Boiling transport is also altered by the smaller adhesion force acting on the liquid water. This change explains why nucleate boiling is suppressed on SHPo surfaces. Less thermal energy is required to overcome the liquid attraction to the surface and form a vapor film. This leads to a dramatic decrease in the surface superheat at which transition to film boiling occurs [17]. A stable film can be maintained on the SHPo surface through the range of ΔT where nucleate and transition boiling would normally be observed on smooth surfaces. Correspondingly, q''_w decreases by up to an order of magnitude within this range. Previous researchers have considered horizontal surfaces [18], quenched spheres [17,19], and immersed vertical cylinders [17].

Several conclusions may be obtained from these prior studies. First, superhydrophobic surfaces alter nucleation site density, bubble growth, and bubble detachment. Bubble nucleation begins at

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