



Heterogeneous wetting surfaces with graphitic petal-decorated carbon nanotubes for enhanced flow boiling



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ABSTRACT

Two-phase cooling is widely employed in temperature-sensitive devices for high heat flux dissipation owing to the benefits of latent heat exchange. The objective of this work is to elucidate the subcooled flow boiling characteristics of heterogeneous wetting surfaces using water as the working fluid. Heterogeneous wetting surfaces with alternating parallel stripes of superhydrophobic (SHo) and superhydrophilic (SHi) regions are fabricated with graphitic petal-decorated carbon nanotube (GPCNT) coatings. Graphitic petals are a carbon nanostructure comprising of stacks of graphene layers standing vertically on a substrate. GPCNTs are synthesized on bulk copper substrates by a two-step microwave plasma enhanced chemical vapor deposition technique. A combination of Teflon coating, shadow mask, and oxygen plasma treatment is utilized to create composite wetting surfaces with differing superhydrophilic area fractions and SHo to SHi channel width ratios. Boiling experiments reveal that heterogeneous wetting surfaces with higher superhydrophilic area fraction (0.66 and 0.85) exhibit significant reduction in surface superheat and higher heat transfer coefficients throughout the entire boiling regime as opposed to uniform SHo and SHi boiling surfaces. Flow visualization reveals enhanced active nucleation site density and preferential bubble nucleation in the superhydrophobic channels of composite wetting surfaces. Isolated near-spherical vapor morphologies on surfaces with higher superhydrophilic area fraction promote thin film evaporation and enhanced bubble ebullition cycles, thereby leading to improved two-phase thermal performance.

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1. Introduction

Design and optimization of boiling surfaces across the wide range of practically relevant heat fluxes and temperatures is a challenging problem. Three cardinal requisites of a boiling surface include low boiling incipience superheat, high heat transfer coefficients (HTC) throughout the range of heat fluxes, and high critical heat flux (CHF). Boiling surfaces with uniform surface wetting typically do not simultaneously satisfy all the aforementioned characteristics. In general, uniformly hydrophilic boiling surfaces, characterized by contact angle $\theta < 90^\circ$, exhibit high CHF values, but a delayed boiling incipience and suppressed heat transfer coefficients at low heat fluxes. In contrast, homogeneously hydrophobic boiling surfaces ($\theta > 90^\circ$) show earlier onset of nucleate boiling and high heat transfer coefficients at low heat fluxes; however, CHF values are lower due to pronounced bubble coalescence and formation of a blanketing vapor layer on the surface.

The effect of surface wetting on the aforementioned characteristics of the boiling curve has been well studied in prior work [1–3]. Phan et al. [1] employed nanostructured coatings synthesized from different materials and deposition methods to obtain boiling surfaces with a range of contact angles (22° – 112°). In the case of relatively hydrophobic surfaces, vapor bubbles formed at low incipient heat flux, but did not detach from the surface and coalesced with bubbles at neighboring nucleation sites. In contrast, hydrophilic surfaces typically exhibited a sustained bubble ebullition cycle. Enhanced surface wetting led to an increase in bubble departure diameter and a dampened bubble emission frequency. Takata et al. [2] conducted pool boiling experiments on a superhydrophobic (SHo) surface made of fine particles of nickel and polytetrafluoroethylene (PTFE) with a contact angle of 152° . In both saturated and subcooled fluid conditions, the nucleate boiling regime was bypassed, and bubble coalescence eventually led to CHF. The reported CHF was dependent on the fluid subcooling and always less than 30 W/cm^2 . In another contrasting study, Takata et al. [3] observed that the pool boiling CHF of copper surfaces sputtered with superhydrophilic (SHi) TiO_2 coatings is about 1.5–2 times larger than those of the uncoated surface.

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Nomenclature

CHF	critical heat flux, W/m ²	W	width of a superhydrophobic or superhydrophilic channel, m
dx	infinitesimal distance, m		
G	mass velocity, kg/m ² s		
HTC	heat transfer coefficient, W/m ² K	<i>Greek symbols</i>	
P_{in}	fluid pressure at the inlet of the flow boiling module, Pa	γ	interfacial tension, N/m ²
q''	heat flux, W/m ²	γ	hydrophilic domain
SHiAF	superhydrophilic area fraction of mixed wetting substrate	δ	hydrophobic domain
T_1	surface temperature of copper substrate, °C	θ	contact angle of the surface
T_2	surface temperature of copper substrate, °C		
T_{in}	fluid temperature at the inlet of the flow boiling module, °C	<i>Subscripts</i>	
T_{out}	fluid temperature at the outlet of the flow boiling module, °C	l	liquid
T_s	mean surface temperature of copper substrate in flow boiling experimental setup, °C	lv	liquid–vapor interface
T_{sat}	saturation temperature, °C	SHi	superhydrophobic
\dot{V}_l	volumetric flow rate of liquid, m ³ /s	SHo	superhydrophilic
V_l	volume of liquid droplet, m ³	sat	saturation temperature
V_v	volume of vapor bubble, m ³	w	wall
		v	vapor

Single bubble dynamics studies carried out by Nam et al. [4] in the case of superhydrophilic and hydrophobic surfaces with artificial nucleation sites revealed contrasting mechanisms of bubble growth and departure. The bubble growth period observed for superhydrophilic surfaces (contact angle $<10^\circ$) was four times shorter while the departure diameter was 2.5 times smaller than a regular hydrophilic surface (with contact angles between 40° – 60°). Okawa et al. [5] reported that a SHi surface results in a near spherical shape of the bubble and leads to enhanced evaporation at the liquid–vapor interface. On the other hand, Nam et al. [6] recorded that hydrophobic surfaces exhibited extremely long growth periods as opposed to a moderate hydrophilic surface. Further, the larger bubble–surface contact area increased the surface tensions forces, delaying bubble departure. When subcooled conditions exist, condensation at the liquid–vapor interface at the top of the bubbles further limited their growth, thereby hindering the departure of bubbles from hydrophobic surfaces [2,6].

Heterogeneous wetting surfaces exhibit more than one distinct contact angle in different regions of the same surface. By controlling the area fraction and patterning of hydrophobic and hydrophilic regions, an improved boiling surface can be obtained [7–11]. Betz et al. [7] studied the pool boiling performance of mixed hydrophobic and hydrophilic surfaces and demonstrated both improved HTC and CHF compared to homogeneously hydrophobic/hydrophilic surface. A mixed surface with hexagonal hydrophobic spots in an otherwise hydrophilic surface exhibited 65% and 100% improvement in CHF and HTC, respectively, as opposed to a homogeneously hydrophilic surface with a uniform 7° wetting angle. Jo et al. [11] conducted pool boiling experiments on combined hydrophilic (54°) and hydrophobic (123°) surfaces devoid of microstructures which revealed enhanced nucleate boiling in mixed wetting surfaces when compared to a homogeneous wetting surface. The number of hydrophobic dots (on an otherwise hydrophilic surface) and the pitch distance between dots were found to be the key parameters determining boiling enhancement. In recent work by Betz et al. [8], enhanced wettability contrast between the hydrophobic and hydrophilic regions (*i.e.*, heterogeneous wetting surfaces fabricated by juxtaposing SHi and SHo regions, termed as ‘superbiphilic’ surfaces) were demonstrated to further enhance pool boiling performance. Hsu et al. [9] assessed pool boiling heat transfer from composite surfaces with interlaced

wettability. Contradictory to the trend observed by Betz et al. [8], they reported higher CHF when the difference in contact angles between the (relatively) hydrophobic and hydrophilic regions is smaller. Takata et al. [10] investigated the pool boiling performance of mixed wetting surfaces with checkered and spotted hydrophobic patterns made of PTFE on an otherwise hydrophilic TiO₂-coated copper substrate. Their major findings include: (1) nucleate boiling is enhanced with reduction in the hydrophobic spot size; and (2) the size of the bubbles departing from the hydrophobic region is determined by the spot size of the hydrophobic pattern.

Alternately, nanostructured coatings present a new approach to engineer the advantages of multiple means of promoting boiling heat transfer. High surface area to volume ratio in nanostructures promotes a thermal fin effect. Nanoscale fabrication methods often create abundant microscale and nanoscale cavities that favor seeding and nucleation of vapor embryos, thereby positively influencing nucleation site density. The nanoscale pore sizes also result in high capillary forces that contribute to rapid rewetting of the surface, potentially reducing the waiting time for bubble growth. A large body of prior work has examined the pool boiling performance of nanostructured coatings, including copper [12,13] and silicon nanowires [12], carbon nanotubes (CNTs) [14], TiO₂ nanotubes [15], flower-like CuO [16], ZnO [17], and nanostructures deposited on the surface due to boiling with nanofluids [1,18]. Few scientific studies have investigated the merits and demerits of employing nanostructured surfaces in forced convection boiling. Li et al. [19] reported enhancement in flow boiling heat transfer using silicon nanowires grown on the surface of microchannels by metal-assisted electroless etching. Morshed et al. [20] examined the flow boiling performance of copper nanowires integrated in microchannels. They reported a reduction of 4–12 °C in the surface superheat of copper nanowire samples as opposed to uncoated surfaces. Khanikar et al. [21] and Singh et al. [22] performed subcooled flow boiling experiments on CNT-coated copper microchannels.

Graphitic petals (GPs), a carbon nanostructure comprising stacks of graphene layers standing vertically on a substrate is a relatively new material [23] and has found substantial interest in the research community [24]. The thickness of graphitic petals is about 5 nm (10–20 graphene layers) while the height can be up to 1 μ m. CNTs decorated with graphitic petals are nanostructured

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