



Enhanced pool boiling heat transfer during quenching of water on superhydrophilic porous surfaces: Effects of the surface wickability



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ABSTRACT

Porous surfaces were prepared by chemical etching with hydrofluoric acid on stainless steel spheres. The etched surfaces were shown to be superhydrophilic with near zero static contact angles as well as wickable by taking advantage of the capillary microstructures. Using the capillary tube method, the surface wickability of the etched samples was characterized by the transient absorbed liquid volume and the wicked volume flux. The wickability was able to be varied by controlling the etching time. Quenching experiments were then performed on the unmodified and etched samples in saturated water at atmospheric pressure. It was found that the quenching process is significantly accelerated in the presence of the etched wickable surfaces, because of the enhancement of boiling heat transfer, especially within the transition boiling regime, and improvement in both the critical heat flux (CHF) and Leidenfrost point as well. Even at a relatively high wall superheat, the vapor film is highly destabilized due to the localized evaporation of the wicked liquid in the capillary structures on the etched surfaces, in addition to the effects of increased surface roughness and wettability. It was also shown that the extent of quenching acceleration is closely related to the surface wickability. In the present work, the most wickable surface leads to the fastest quenching with the mostly improved boiling heat transfer. Based on the classical Kandlikar's model, a linear correlation was proposed between the increase ratio of the CHF and the square of the wicking number that quantifies the surface wickability.

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1. Introduction

Pool boiling heat transfer during quenching in water has long been studied with applications to a variety of industrial processes, such as heat treatment of steel and safety of nuclear reactors [1]. Enhancement of the critical heat flux (CHF) in pool boiling can be achieved by surface modification [2]. Accelerated quenching with enhanced CHF has been extensively observed on modified surfaces via passive deposition of nanoparticles during quenching (using nanofluids prepared by nanoparticles in various materials, sizes and shapes [3–8]) or active surface structuring prior to quenching (using various surface modification technologies including spray coating, laser machining and anodic oxidation [9–15]), leading to favorable changes in surface properties such as roughness, wettability and capillarity.

Although the exact contribution of each of these interrelated surface properties has not yet been clarified, surfaces that are capable of wicking liquid by capillary structures (e.g., small pores or channels) appear to have a great potential for CHF enhancement [2]. The spontaneous in-plane transport of liquid, which is driven by liquid absorption into the capillary spaces through capillary action (or wicking) [16], serves as an additional mechanism to rewet the dry spots on a boiling surface. The study of capillary wicking effect on pool boiling CHF, as can be dated back to the 1960s [17], has received increasing attention during the past decade [2]. This is attributed to the technical advances that allow for convenient and large-scale fabrication of surfaces with micro-/nano-structures to take advantage of capillary wicking [18,19].

The role of capillary wicking on CHF phenomena can be understood intuitively through modification of the classical Kandlikar's CHF model [20] by involving the capillary force as an additional term in the force balance analysis [21]. Therefore, a great number of efforts have been dedicated to building a quantitative relationship between capillary wicking flow and its induced CHF enhancement. Although capillary wicking phenomena can be readily observed, there are difficulties associated with direct experimental

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Nomenclature

c_p	specific heat capacity (J/kg K)
d	inner diameter (μm)
D	diameter of wicked area (μm)
g	gravitational acceleration (m/s^2)
h	height (μm)
H_{fg}	latent heat of evaporation (J/kg)
k	thermal conductivity (W/m K)
K	coefficient (–)
n	integer number
q''	heat flux (W/m^2)
r	radial axis (mm)
R	radius (mm)
R'	dimensionless radius
t	time (s)
T	temperature ($^\circ\text{C}$)
U	wicked volume flux ($\mu\text{L}/\text{mm}^2 \text{ s}$)
V	absorbed liquid volume (μL)

Greek symbols

α	thermal diffusivity (m^2/s)
β	ratio of solid-liquid contact area relative to the sphere area
ϕ	inclined angle ($^\circ$)
θ	contact angle ($^\circ$)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

c	center
CHF	critical heat flux
l	liquid
s	surface
sat	saturation
v	vapor

determination on the velocity or mass flux (i.e., flow rate) of capillary wicking flow on modified surfaces. Methods based on two types of principles, either liquid uptake [22–24] or droplet spreading [25–28], were proposed to quantify capillary wicking ability of the modified surfaces. The extra CHF increase resulted from capillary wicking was in general correlated to the wicking ability through modification of the Kandlikar's model. These methods are simple and intuitive, because the required estimation on either the wicking coefficient or the wicking velocity can be readily done with the aid of a high-speed camera. However, the accuracy of these methods is significantly affected by the isotropy of the modified surfaces as well as the presence of empirical geometric parameters in the models, such as the surface roughness factor and liquid microlayer thickness.

In order to avoid all these complexities, a novel method for quantifying the capillary wicking ability was proposed by directly measuring the absorbed volume on a wicking surface from the liquid supply of a capillary tube [29]. The two-dimensional liquid spreading/wicking on the surface is transformed to the one-dimensional liquid level drop in the thin capillary tube. This level drop can be accurately measured using a high-speed camera to determine the absorbed volume flux (i.e., rate of capillary wicking flow) without any beforehand knowledge on geometric parameters of the surfaces. A straightforward relationship was then built between the wicked volume rate and the CHF gain due to evaporation of this extra amount of liquid supply to the boiling surfaces. This direct method was adopted by another group of researchers to provide a quantitative measure of the wickability of micro-/nano-structured superhydrophilic surfaces with a variety of substrate materials, surface foulings, structure materials, morphologies, and structure scales [30]. As inspired by the nondimensional grouping for CHF, a phenomenological parameter was proposed to nondimensionalize the wicked volume flux. This nondimensional grouping was referred to as the wicking number (Wi) for wickability, which is analogous to the contact angle for wettability. Using the experimental data from more than three dozens of individual surfaces, the measured CHF (up to a record high value of $2570 \text{ kW}/\text{m}^2$) was shown to have an almost linear dependence on the wicked volume flux, indicating that the wickability (or wicking number) is the single key factor in dominating CHF on superhydrophilic surfaces that all have a zero static contact angle but with distinct wickabilities. In a recent work [31], by performing pool boiling experiments on carefully engineered nanoporous hydrophilic surfaces with independently controlled pore size and

porous layer thickness, it was concluded that the wickability may not be the only factor dictating CHF on nanoporous hydrophilic surfaces, which is in fact determined by the competition between heat conduction in the capillary structures and wickability.

Having given insights into the capillary wicking effect on pool boiling CHF by the above-mentioned efforts (all through steady-state heating experiments), however, understanding of the influence of capillary wicking on pool boiling during cool-down of a quenching process, especially on the film and transition boiling regimes, is relatively deficient. For example, in a recent work [32], quenching experiments were carried out on spheres with a microstructured porous surface. The major attention, however, was paid to the observed increase of the Leidenfrost point (LFP), referred to as the minimum film boiling temperature, on such surface. The increase of LFP was attributed to the fin effect associated with the microstructures that facilitates liquid-solid contact during quenching. Despite the likely presence of capillary wicking due to the microporous structures, however, pool boiling heat transfer during quenching was not even tried to relate to the surface wickability.

In order to extend the existing knowledge, quenching and pool boiling behaviors were studied experimentally on superhydrophilic porous surfaces with various wickabilities. The primary objective of the present work is to reveal the effects of wickability on film and transition boiling behaviors, and on the LFP and CHF during quenching as well.

2. Experimental

2.1. Surface preparation and characterization

Small spheres, having a diameter of 10 mm and made of 304 stainless steel, were used in the quenching experiments. The surfaces of the sphere samples were modified following a facile chemical etching protocol [33]. Prior to surface modification, the original sphere samples were rinsed carefully by acetone, ethanol and deionized water in sequence. The cleaned samples were dipped in a hydrofluoric (HF) acid solution (concentration $\sim 50\%$) for etching, while keeping the solution temperature at $50 \text{ }^\circ\text{C}$. The surface wickability achieved was varied by controlling the time duration of etching (from 1.5 min to 4.0 min). The etched samples were then removed from the acid solution and allowed for natural air drying at ambient conditions.

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