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Regulated transient pool boiling of water during quenching on nanostructured surfaces with modified wettability from superhydrophilic to superhydrophobic

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ABSTRACT

The effects of surface wettability, from superhydrophilic to superhydrophobic, on transient pool boiling of water under atmospheric pressure were experimentally examined by means of the quenching method with hot stainless steel spheres. The wettability changes, with a contact angle ranging from nearly 0° to more than 160°, were realized by nanostructured coating on the spheres. The quenching cooling rate was shown to slow down with increasing the contact angle as the vapor film was stabilized and retained by surface hydrophobicity even at very low wall superheats. Remarkable boiling heat transfer enhancement, with critical heat flux (CHF) increase up to nearly 70%, was achieved for the superhydrophilic case as compared to the original hydrophilic baseline case. As observed by high-speed imaging on the dynamic quenching processes, violent rewetting that stems from superhydrophilicity facilitated early collapse of the vapor film, thus leading to the great increase in film boiling heat transfer and CHF. The observations suggested an active means of regulation of transient pool boiling by employing the nanostructured surfaces with modified wettability to the extremes, toward either enhanced boiling heat transfer or retention of stable film boiling phase.

1. Introduction

As a highly-efficient heat transfer mode involving intensive liquid/vapor phase change [1], boiling has long been studied and practiced toward thermal energy conversion and management. Transient pool boiling during quenching processes has found numerous industrial applications from materials processing to thermal management of nuclear reactors. In laboratory experiments, the quenching method enable a rapid and easy means of establishment of complete boiling curves, encompassing the film, transition, and nucleate boiling regimes [2]. The critical heat flux (CHF) and Leidenfrost point (LFP) along with its associated minimum heat flux (MHF) can also been readily reduced from the quenching data. In the literature, enhancement of pool boiling with respect to the representative boiling regimes and critical points has been studied for decades. Recent efforts on pool boiling heat transfer enhancement, especially the CHF enhancement [3], may be classified into two categories: (a) utilization of nanoparticle suspensions (nanofluids) [4–6] and (b) boiling surface modification with micro-/nanostructures [7–9]. Experimental evidence has revealed the mechanisms of pool boiling enhancement of nanofluids as a result of modification of the boiling surface properties, wettability for example [10–13], due to deposition of nanoparticles. This indicates that the utilization of nanofluids for enhanced pool boiling may be considered as a passive approach to boiling surface modification.

Three predominant boiling surface properties, i.e., roughness, porosity, and wettability, have been identified to have separate effects on boiling heat transfer [14,15], among which the wettability, usually quantified by a contact angle, has mostly been explored from thermodynamic point of view. A low contact angle, i.e., good wettability (or hydrophilicity), is preferred to enhance the CHF, whereas hydrophobicity, represented by a high contact angle, is desirable to retain the stable film boiling phase [16]. Since the primary phase change modes during nucleate (and CHF) and film boiling (and LFP and MHF) regimes are essentially different, there is no simple guide to expect how a transient pool boiling process is regulated through modification of wettability of the boiling surface. Concurrent with the development of advanced nanomaterials, the emergence of micro-/nanostructured superhydrophilic (contact angle < 10°) and superhydrophobic (contact angle > 150°)

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Nomenclature

A	area, mm^2
Bi	Biot number
c_p	specific heat, kJ/kg K
D	diameter, mm
g	gravitational acceleration, m/s^2
h	heat transfer coefficient, W/m^2 K
H	latent heat of evaporation, kJ/kg
Ja	Jakob number
k	thermal conductivity, W/m K
Nu	Nusselt number
q''	heat flux, kW/m^2
Ra	Rayleigh number
R_a	roughness parameter (average of absolute values), μm
R_q	roughness parameter (root mean squared), μm
t	time, s
T	temperature, °C (or K)
V	volume, mm^3

Greek symbols

α	thermal diffusivity, m^2/s
δ	vapor film thickness, μm
ϕ	inclination angle, °
μ	dynamic viscosity, Ns/m
ν	kinematic viscosity, m^2/s
θ	contact angle, °
ρ	density, kg/m^3
σ	surface tension, N/m
ξ	azimuthal anlge from sphere bottom, °

Subscripts

CHF	critical heat flux
h	hydrostatic
l	liquid
sat	saturation
t	thermodynamic
v	vapor

surfaces have enabled modification of surface wettability to the extremes [17]. This has led to a great number of emerging applications involving liquid/vapor phase change at surfaces, i.e., boiling, evaporation, and condensation, that significantly, or even completely, departs from the traditional phenomena [18,19]. Therefore, the effects of superhydrophilicity and superhydrophobicity on transient pool boiling and their comparison to boiling on conventional hydrophilic and hydrophobic surfaces are of great interest [20].

In this paper, we report on preliminary experimental results of transient pool boiling of saturated water at atmospheric pressure during quenching on surfaces with modified wettability from superhydrophilic to superhydrophobic. In Section 2, the quenching apparatus and test procedure are described, followed by a detailed presentation of preparation and characterization of the surfaces with various wettabilities. The experimental results of the quenching curves and boiling curves are reported in Section 3. Data analysis and interpretation are presented in Section 4, with an emphasis on variations of the CHF, LFP (and MHF), average surface heat transfer coefficient, and equivalent vapor film thickness and their comparison to existing models.

2. Experimental

2.1. Quenching apparatus and test procedure

Quenching tests of hot spheres in a water pool were carried out to study the transient pool boiling. A quenching apparatus, featuring compactness, visualization, and ease of control, was designed and constructed to perform visualized quenching experiments at atmospheric pressure. A side-view photograph of the experimental setup is shown in Fig. 1a. The quenching apparatus consisted of various components, including an electric actuator

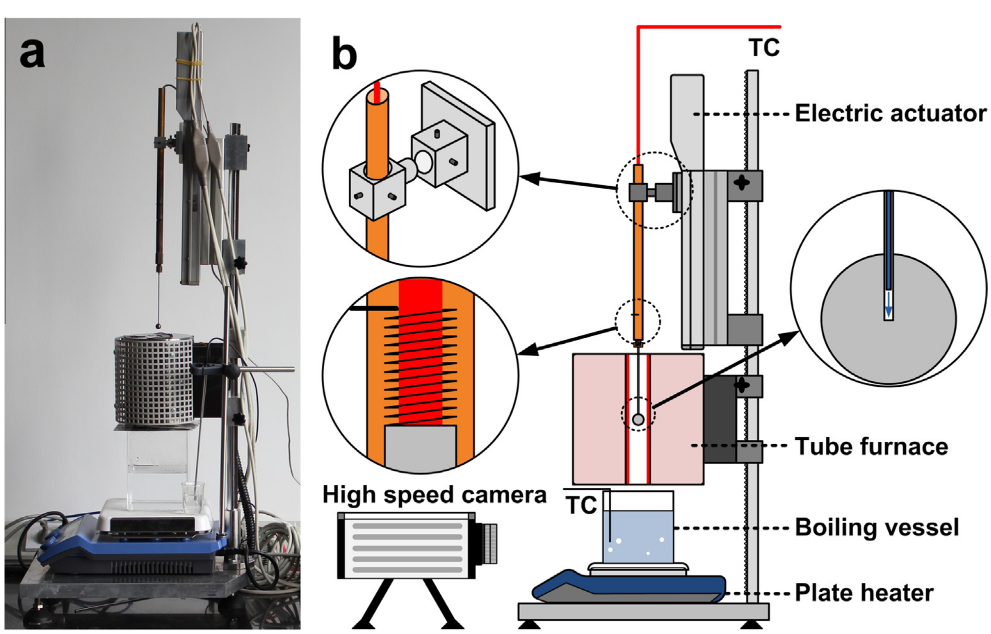

Fig. 1. Experimental setup of the quenching facility: (a) photograph and (b) schematic diagram with magnified insets showing parts assembly.