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Smart surface in pool boiling: Thermally-induced wetting transition

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ABSTRACT

The boiling heat transfer coefficient (HTC) and critical heat flux (CHF) of a TiO_2-coated surface (TCS) were investigated in pool boiling with increasing saturated temperature at the pressurized conditions ranged from 1.0 to 4.1 bar. TCS increased HTC in comparison with a reference surface coated with SiO_2 (SCS) under the pressure ranged from 1.0 to 4.1 bars. CHF of TCS was higher than SCS at pressure of 4.1 bar while lower below 4.1 bar. Measurement of the contact angle of a water droplet on the tested surfaces after heat treatment showed a wettability increase of TCS, a contact angle reduction from 83.1° to 32.7° when the heat treatment temperature changed from 100 °C to 200 °C. No such change was observed for SCS. This contact angle change after heating suggests that the wetting transition of TCS is a key factor in the enhancement of both HTC and CHF in boiling. TCS is hydrophobic at a low wall temperature and becomes hydrophilic as the wall temperature increases. Hydrophobicity of TCS at low wall temperatures explains the improved HTC over SCS near the boiling inception point and low heat flux regime, and hydrophilicity at high wall temperatures explains the increase of CHF. The transition in the wettability of TiO_2 appeared to be involved in CHF enhancement. The thermally-induced wetting transition of TiO_2 provides a simple and innovative means for enhancing both HTC and CHF with no additional treatment; as such, we refer to TiO_2 as a 'smart' surface.

1. Introduction

Nucleate boiling is one of the most efficient heat-transfer methods. In evaluating boiling performance, heat transfer coefficient (HTC) and critical heat flux (CHF) are important measures. HTC is an index for the efficiency of the heat transfer and CHF is a limitation on the available nucleate boiling regime. Thus, many techniques have been assessed to enhance boiling performance for the efficiency and safety of heat transfer systems.

Recently, the wettability of the heating surface has been a focus because it has an important effect on boiling performance. A hydrophobic surface activates bubble generation more vigorously than a hydrophilic surface; thus, it contributes to higher HTC. However, a hydrophilic surface induces liquid supply to the dry area of a heating surface, delaying CHF. Wettability can be controlled by modifying the morphology and/or chemical composition of a surface [1–3]. There are many reports on enhancing boiling performance by controlling wettability in pool boiling.

Forrest et al. [4] controlled the wettability of nickel wires using a layer-by-layer (LbL) method and examined the boiling characteristics of these wires. Hydrophobic wires showed much higher HTCs, but lower CHF value than hydrophilic wires. Superhydrophilic wires showed the highest CHF (enhanced by 101%) although they had lower HTCs than hydrophobic wires. Bourdon et al. [5] investigated the wettability effect using surfaces having nanometer roughness to isolate the effect; bronze plates were highly polished and grafted using an alkanethiol self-assembled monolayer (SAM) to control wettability. From pool boiling results, hydrophobic surfaces showed higher HTCs, but lower CHFs than hydrophilic surfaces [5]. Bourdon et al. [6] conducted similar experiments using glass substrates with chemical grafting using SAMs of octadecyltrichlorosilane (OTS) and identified higher HTCs and lower CHFs than hydrophilic surfaces; their results were consistent with previous work [5]. From the literatures, hydrophobic surfaces induce active bubble generation at low wall superheat, but cause premature CHFs due to excessive bubbles, despite low wall superheat. Thus, if the premature CHF of hydrophobic surfaces could be overcome, then it would be practical for higher heat-transfer-performance surfaces with higher HTCs than hydrophilic surfaces.

Hydrophilic surfaces promote liquid supply to the surface, contributing to a higher CHF than a hydrophobic surface. In You et al. [7], a nanofluid was examined because it enhanced CHF. Bang et al.

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Nomenclature

A_1	experimental constant
A_2	experimental constant
A_h	effective heating area, m^2
B	experimental constant
c_{pl}	heat capacity, kJ/kg·K
C_{simple}	simplified experimental constant
CHF	critical heat flux, kW/m^2
F	experimental constant
g	gravity acceleration, m/s^2
h_{lv}	latent heat, kJ/kg
HTC	heat transfer coefficient, $kW/m^2 \cdot K$
I	current, A
k_l	thermal conductivity, W/m·K
m	exponent
P	pressure, bar
P_{sat}	saturated pressure, bar
q''	heat flux, kW/m^2
q''_{CHF}	critical heat flux, kW/m^2
R_s	resistance of shunt resistor, Ω
SCS	SiO_2-coated surface
T_b	bulk temperature of water, °C
T_h	temperature of the heating element, °C
T_{sat}	saturated temperature, °C
T_w	wall temperature, °C
TCS	TiO_2-coated surface
V_h	voltage of the heating element, V
V_r	voltage of the shunt resistance, Ω

Greek symbols

β	receding contact angle, °
ϕ	orientation of heating surface, °
μ_l	viscosity, μPa·s
θ	static contact angle
ρ_l	liquid density, kg/m^3
ρ_v	vapor density, kg/m^3
σ	surface tension, N/m

Subscripts

l	liquid
v	vapor
lv	phase change from liquid to vapor
w	wall of heated surface
b	bulk
sat	saturated condition
h	heating element
CHF	CHF

[8] used an Al_2O_3 nanofluid as a working fluid and conducted pool boiling experiments; although nanofluid showed poorer HTC than pure water, the CHF increased regardless of surface orientation. These results were attributed to the deposition of nanoparticles on the heating surface [8]. Kim et al. [9] used pool boiling to examine the effects of deposited nanoparticles on a wire heater; they reported that CHF increased not only on the bare wire in nanofluid boiling but also on nanoparticle-deposited wire in pure water boiling. Kim et al. [10] demonstrated increased wettability due to nanoparticle deposition after boiling in a nanofluid. They reported that nanoparticle deposition enhanced wettability and caused a CHF increase. Stutz et al. [11] and Jo et al. [12] also used nanoparticle-deposited surfaces in pool boiling and reported that the enhanced wettability, due to nanoparticle deposition, increased CHF. Since noting the importance of 'good' wettability of nanoparticle-deposited surfaces in increasing CHF, other types of surface modification techniques have been suggested. Forrest et al. [4] also identified CHF increases on a hydrophilic surface by the LbL method in pool boiling. Kim et al. [13] fabricated nano- and microstructures using a microelectromechanical system (MEMS) technique and conducted pool boiling on these structured surfaces. Microstructures showed the highest HTC, and/or nano/micro-combined structures showed the highest CHF (107% enhancement). The increase in CHF was facilitated by enhanced wettability due to the nanostructures [13]. Ahn et al. [14] made micro/nano-multiscale structures on zircaloy-4 surfaces using anodic oxidation; the contact angle on the surface was <10° due to increased wettability. From pool boiling experiments, they also reported increased CHF and attributed that to a spreading effect of the liquid.

From experimental evidences [4–6,15,16], a hydrophobic surface can trigger nucleate boiling at low wall superheat, but it also brings premature CHF due to bubble coalescence and sticking to the surface. In contrast, a hydrophilic surface can promote liquid supply to the dry area to delay CHF. In this respect, heterogeneous wetting control techniques have been developed. Betz et al. [17,18] developed heterogeneous wetting surfaces that had hydrophobic islands on a hydrophilic network or hydrophilic islands on a hydrophobic network. Their investigation of pool boiling performance confirmed that hydrophobic islands with hydrophilic networks showed the best boiling performance and enhancement of the HTC and CHF by 100% and 65%, respectively. Jo et al. [15,19] also prepared heterogeneous wetting surfaces and examined their boiling performance; they showed that the hydrophobic surface had a higher HTC with sustaining CHF. Using a surface with hydrophobic dots on a hydrophilic substrate, they enhanced HTC without degradation of CHF.

Although wettability can affect boiling performance, there is a trade-off between HTC and CHF. In this respect, Bertossi et al. [20] used switchable polymers coating for the improvement of boiling heat transfer. The polymer coating showed wetting transition of hydrophilic to hydrophobic when a temperature is above 108 °C. Since hydrophobic surface promotes initiation of bubble nucleation while hydrophilic surface enhanced bubble detachment, the polymer coating increased boiling heat transfer in the nucleate boiling regime.

In the present study, TiO_2 thin film was used to enhance both HTC and CHF. Sun et al. [21] fabricated thin films of TiO_2 on glass substrates to investigate wettability changes after heat treatment at various temperatures in air. The initial water contact angle on TiO_2 was 54°. The contact angle decreased as the heat treatment temperature increased. When TiO_2 was annealed at 200 °C, the contact angle was ~20°. In addition, the contact angle decreased to <10° with increasing heat treatment temperature, up to about 250 °C. They reported that oxygen vacancies in the crystal structure of TiO_2 primarily improved wettability. Such oxygen vacancies can be generated in the crystal structure of TiO_2 when it is treated by ultraviolet (UV) irradiation, heat treatment, and Ar^+ sputtering. They explained that oxygen vacancies were kinetically favorable for adsorption of hydroxyl, and water molecules were adsorbed dissociatively on the oxygen vacancies. The special characteristics of TiO_2 have been reported in numerous studies [22–29].