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Surface wettability effects on critical heat flux of boiling heat transfer using nanoparticle coatings

Chin-Chi Hsu, Ping-Hei Chen *

Department of Mechanical Engineering, National Taiwan University, Taipei 10617, Taiwan

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ABSTRACT

This study investigates the effects of surface wettability on pool boiling heat transfer. Nano-silica particle coatings were used to vary the wettability of the copper surface from superhydrophilic to superhydrophobic by modifying surface topography and chemistry. Experimental results show that critical heat flux (CHF) values are higher in the hydrophilic region. Conversely, CHF values are lower in the hydrophobic region. The experimental CHF data of the modified surface do not fit the classical models. Therefore, this study proposes a simple model to build the nexus between the surface wettability and the growth of bubbles on the heating surface.

1. Introduction

Critical heat flux (CHF) is a significant index in boiling heat transfer research. Many factors, including surface topography, affect the boiling heat transfer. Berenson [1] found that surface roughness affects the nucleation boiling heat transfer because heat transfer efficiency is proportional to surface roughness. Carey [2] investigated the boiling heat transfer by controlling the surface roughness and thickness. Golobic and Ferjancic [3] reported the effects of coating thickness and content on CHF.

The growth and departure of vapor bubbles can also influence the boiling heat transfer [4]. The influence of surface modification increases with the number of microscale cavities available because these cavities serve as the starting sites for the heterogeneous nucleation of liquid for bubble formation [2,5]. These cavities generally range in size from tens to hundreds of micrometers [6].

A number of studies have reported that surface wettability is an important factor affecting the boiling heat transfer [7–9]. Phan et al. [7] reported that surface wettability plays an important role in bubble growth: a lower CA surface increases the bubble departure diameter. The contact angle (CA, θ) has a very strong influence on transition boiling [10], and a hydrophilic surface increases the CHF in boiling heat transfer. Dhir and Liaw [11,12] reported good agreement between theoretical predictions of CHF with experimental data in the hydrophilic region. Kim et al. [13] reported that CHF enhancement in nanofluids is the results of nanoparticle deposition on the surface, and that this nanoparticle deposition significantly increases surface wettability. Therefore, surface wettability is a crucial factor in boiling heat transfer. Thin-film coatings with alumina [14], zirconia [14], and silica [14,15] nanoparticles on the heating surface lead to significant enhancement in the pool boiling CHF. Chen et al. [16] reported that a superhydrophilic surface made by nanowire arrays on an Si and Cu substrate can be used to increase the CHF by more than 100%. Therefore, surface wettability has been a major subject of research on boiling heat transfer. This study applies the heating method of altering the surface nature to affect the CHF of surfaces with different wettability characteristics. Nano-silica particles (40 nm) were coated on the heated surface, resulting in different levels of wettability. The non-wetting surface effect on the pool boiling heat transfer is substantially less, especially on superhydrophobic surfaces. This study introduces the effects of changing the surface wettability from superhydrophilic to superhydrophobic on boiling heat transfer.

2. Thermal system

Fig. 1 illustrates the setup of the thermal system of CHF experiment. This system consisted of a copper block measuring 1.6 cm × 1.6 cm × 1.6 cm, with holes drilled 0.7 mm deep on the sides of the copper block. A thermocouple (0.6 mm) was placed in each of these holes with sink grease to reduce the contact

* Corresponding author. Address: Department of Mechanical Engineering, National Taiwan University, No. 1, Roosevelt Road Sec. 4, Taipei 10617, Taiwan. Tel.: +886 2 33662689; fax: +886 2 23670781/23631755.

E-mail address: phchen@ntu.edu.tw (P.-H. Chen).

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Nomenclature

C	Zuber constant
K	thermal conductivity (W/mK)
g	gravitational acceleration (m/s^2)
H	heat transfer coefficient (W/m^2 K)
h	heat of vaporization (kJ/kg)
q	heat flux density (kW/m^2)
T	temperature (K)
ΔT	wall superheat (K)

Greek symbols

β	growth bubbles fraction
θ	contact angle, degree
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension of liquid (N/m)

Subscripts

b	bubble
c	correctional equation
d	distance
l	liquid
v	vapor
lv	liquid–vapor
fb	film boiling
w	wall
sat	saturation
z	Zuber
1	up side
2	down side

Abbreviations

CHF	critical heat flux
CA	contact angle

resistance. The holes were positioned on the top, middle, and bottom of the block, and each hole was separated by 7.5 mm. The top of the copper block was the heated surface with a different surface wettability after modification. One side of the heated block was coated with fiberglass for heat insulation. A glass tank (10 cm × 10 cm × 25 cm) sat on top of the heated block. The opening on the top of the tank maintained atmospheric pressure and the pool temperature was naturally adjusted to the saturated temperature (100 °C). On the top of the tank, a camera was used capture photos of bubble growth. A heat source consisting of four 200 W electric heating rods was placed under the heated block. This heating source was controlled by an electricity-supplier. After heating the surface, the thermometer recorder acquired data from the thermocouples and transferred it to the computer for analysis. The temperature difference was obtained from the two positions of the temperatures data. Once the distance difference (Δx) of these two positions and copper thermal conductivity was determined, Fourier's law (1) was used to calculate the heat flux into the boiling liquid. Uncertainties of experimental measurement of heat flux and wall superheat were estimated using Eqs. (2) and (3). The parameters Uq, U_{T2-T1}, and $U_{\Delta x}$ in these equations represent the uncertainties of the heat flux q, and parameters Uq and $U_{T0-T\mathrm{sat}}$

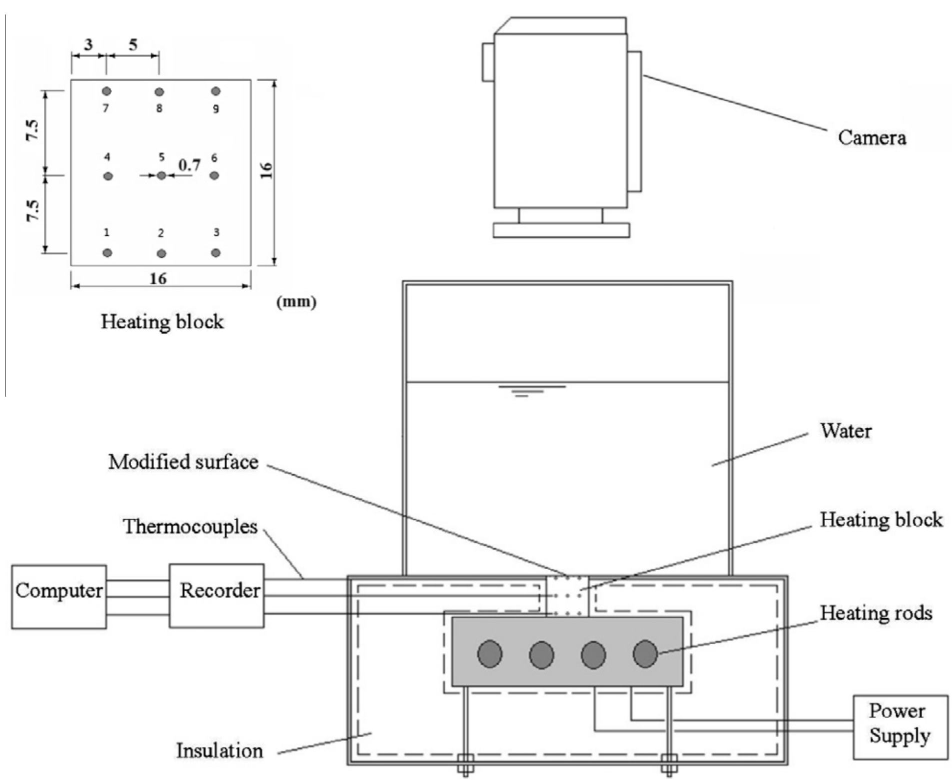

Fig. 1. Experimental facility setup.