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A new CHF model for enhanced pool boiling heat transfer on surfaces with micro-scale roughness

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ABSTRACT

A new CHF model was developed for saturated pool boiling on surfaces with micro-scale roughness, including micro-pillar, micro-ridge structures as well as random roughness made by emery paper or sandpapers. The model accounted for the effects of roughness-augmented wettability and capillary wicking on CHF enhancement. Geometric size parameters of well-defined micro structures were explicitly included in the correlation of present model, which was then extended to include randomly roughened surfaces based on the equivalent geometric sizes obtained from roughness parameter, Ra. The present model was evaluated by comparing with 104 CHF data in literatures with different working fluids, surface materials and surface morphologies. The results showed that present model could match most of the data within 25% and the overall mean absolute error was 13.7%. Particularly, the present model was capable of predicting the decrease trend of CHF with increase of roughness factor appeared in experimental studies and this trend was not reflected in previous models. The present study was expected to improve the understanding of CHF augmentation mechanism on micro-structured surfaces and to provide guidelines for optimal surface design.

1. Introduction

Pool boiling heat transfer is an effective heat dissipation method which has been applied in many industrial sectors, such as the electronic chip cooling and thermal load management of nuclear power plants [1]. The critical heat flux (CHF) represents the upper limit of nucleate boiling, which has a much higher heat transfer coefficient (HTC) than single phase convection due to the effects of bubble dynamics and latent heat of vaporization [2]. After a boiling surface reaches CHF, it will be enveloped by a layer of vapor which has relatively low thermal conductivity, thus deteriorating the HTC and raising the surface temperature. Failure of thermal systems may occur if the temperature of heat transfer surface exceeds its operational limit [3–5]. Therefore it is crucial to understand the mechanisms triggering CHF as well as to develop techniques to enhance CHF [6].

Traditional theories of CHF phenomenon were based on far-field factors, i.e. the hydrodynamic aspect of boiling. Kutateladze [7] and Zuber [8] considered the Kelvin-Helmholtz instability between the ascending vapor columns and descending liquid flow. When the relative velocity between the two phases exceeds a critical value the hydrodynamic stability would be broken and CHF condition is reached. They developed identical CHF correlations for horizontal smooth boiling surface with an infinite area

$$q_C = K \cdot h_{fg}\rho_g^{0.5}(\sigma g \Delta\rho)^{0.25} \tag{1}$$

where the constant K varies from 0.131 to 0.18. Haramura and Katto [9] proposed the macrolayer model which presumed that CHF occurs when the liquid layer under the bubble mushroom completely evaporates. Although these hydrodynamically based models provided fundamental physical understanding about the mechanism of CHF phenomenon, they did not incorporate the important role played by boiling surface. At CHF, complex thermodynamic and hydrodynamic interactions between the solid, liquid and vapor exist near the boiling surface. The effects of boiling surface properties must be included in a robust and widely applicable CHF model.

A variety of experimental studies highlighted the effects of boiling surface on CHF. The thermal properties, orientation, geometric size [10] and surface characteristics [11–13] of the heater can considerably influence the values of CHF. The surface characteristics of a heater directly influence the dynamic interactions between liquid and vapor therefore can modulate the boiling process and CHF values. Usually wettability, porosity and roughness were considered as the surface characteristics and O'Hanley et al. [14] suggested the three factors be independently investigated to optimize the

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Nomenclature

d	diameter of circular pillars; side length of square pillars; width of ridges, m
D_a	diameter of triple contact line, m
g	gravitational constant, $kg \cdot m/s^2$
h	height of micro-pillars, m
h_{fg}	vaporization heat, J/kg
K	the factor in Zuber's correlation, dimensionless
M	the multiplier in Eqs. (11) and (13), dimensionless
P	center-to-center pitches between micro pillars, m
q	heat flux, W/m^2
r	roughness factor, dimensionless
Ra	average roughness, m
S	the multiplier in Eq. (6), dimensionless
Sm	mean spacing between adjacent peaks, m
u	velocity of capillary induced liquid flow, m/s

Greek

θ	contact angle, degree
φ	inclined angle of boiling surface, degree
ρ	density of liquid and vapor, kg/m^3
σ	surface tension, N/m
$\Delta\rho$	density difference between liquid and vapor, kg/m^3
Φ	solid fraction, dimensionless
α	included angle between pillar arrays, degree

Superscript

*	apparent contact angle on roughened surfaces
′	additional heat flux term for micro-ridge surfaces

Subscript

add	additional heat flux term corresponding to capillary wicking effects
C	critical heat flux; critical angle for hemi-wicking
g	vapor
K	heat flux term corresponding to Kandlikar's model
l	liquid
rec	dynamic receding angle

surface design. In particular, Kandlikar [15] proposed a widely accepted theoretical correlation of CHF taking into account the effects of contact angle. The model was based on the force balance analysis of a bubble at CHF condition and the formula can be expressed by modifying the constant K in Eq. (1)

$$K = \frac{1+\cos\theta_{rec}}{16}\left[\frac{2}{\pi}+\frac{\pi}{4}(1+\cos\theta_{rec})\cos\varphi\right]^{0.5} \tag{2}$$

where θ_{rec} is the dynamic receding angle and φ is inclined angle of the boiling surface. Eq. (2) indicates that CHF increases when the wettability of a surface is improved. Recent studies revealed that the wettability of a surface was not independent but remarkably influenced by the surface morphology [16–18]. Hydrophilic surfaces with micro/nano structures can apparently improve wettability and capillary wicking effects [16–19]. This fact inspired the research efforts of enhancing pool boiling CHF by fabricating different heater surfaces, with the help of development in micro/nano manufacturing techniques. Many researchers reported CHF enhancement using surface modification techniques and the maximum amplification was up to 2–3 folds [2–4,11,12,18,20–33]. The primary advantage of micro/nano structured surfaces is that they can improve the wettability and induce capillary wicking effects, facilitating the rewetting of dry vapor patches. The liquid supply underneath a coalesced bubble is critical to delay the dry-out of heating surface and enhance CHF [10,25]. Several comprehensive reviews on boiling enhancement of micro/nano structured surfaces can be found in Refs. [13,34]. Kim et al. [34] classified the micro/nano manufacturing techniques into four groups: surface mechanical machining, surface coating, chemical process and micro/nano electro mechanical system. Different surface morphologies can be fabricated on boiling surfaces with different materials using these manufacturing techniques, which are readily available.

The objective of this study is to develop a theoretical model predicting the CHF values of surfaces with micro-scale roughness; in particular, surfaces with well-defined micro structures as well as random roughness made from emery paper or sandpapers are considered in this study. The well-defined micro structures are particularly appropriate for systematically studying the roughness-augmented wettability and capillary wicking effects [18,27] because the geometric parameters of micro-structures can be precisely controlled and fabricated. Additionally, randomly roughened surfaces ground by emery paper or sandpapers are more easily produced and are important in practical applications; efforts are also made to model the CHF of these surfaces. The outline of this paper is as follows. Section 2 presents a brief summary of previous CHF studies on micro/nano structured surfaces. The assumption and derivation of the present model are presented in Section 3. In Section 4, the performance of present model is analyzed by comparing it with 104 experimental data points. The summary and conclusion of this paper are given in Section 5.

2. Previous experimental and theoretical studies on micro/nano structured surfaces

2.1. Experiments

You et al. [35] first observed that CHF can be enhanced with nanofluid as a coolant. The CHF of 0.025 g/L Al_2O_3 nanofluid was >3 times that of pure water. Kim et al. [23,36] subsequently demonstrated that the CHF augmentation was caused by the nanoparticle deposition on the boiling surface. The deposited nanoparticles changed the surface characteristics and improved the wettability [17] and induced capillary wicking effects [19], which were responsible for the CHF enhancement. Chen et al. [24] first utilized Si and Cu nanowires to enhance CHF of water. The static contact angle of the nanowire coated surfaces approached to zero and the obtained CHF could not be explained merely by wettability effects. Ahn et al. [3] used anodic oxidation technique to modify surface morphology of zircaloy-4 and the treated surface demonstrated CHF increases beyond Kandlikar's model prediction. Ahn et al. [25] attributed their experimental results to the liquid spreading effect and successfully modeled the data by adding an additional term to Kandlikar's correlation. More recently, surfaces with micro-pillar, micro-hole and micro/nano hierarchical structures were extensively studied and showed outstanding enhancement of CHF [18,26–28,30,32].

Table 1 lists the experimental studies using surfaces with well-defined micro-structures. Also included in Table 1 are studies using surfaces with random roughness made from emery paper or sandpapers. The listed experimental conditions were saturated pool boiling on horizontal surfaces under atmospheric pressure. While most studies showed CHF enhancement with surface roughness, Kim et al. [18] found that CHF decreased with increasing roughness factor r, defined as the ratio of actual liquid-solid contact area to