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An analysis of surface-microstructures effects on heterogeneous nucleation in pool boiling

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ABSTRACT

The interaction of surface microstructures and wettability effects on heterogeneous nucleation in pool boiling is analyzed in this paper based on the changes of free energy and availability. It is shown that the bubble is most easily formed on a concave surface in comparison with a convex surface or a plane surface at the same wettability and the same wall temperature. It is found that the effect of microstructures greatly enhances nucleation of bubbles when the curvature radius of these microstructures is in the range of 5–100 times less than the bubble radius. Larger than this limit, the surface roughness effect is negligible and the wettability effect predominates. Closed form analytical solutions for the critical radius and change in availability are obtained for the special case of homogeneous nucleation where no wall temperature gradient exists on surfaces with microstructures. Under this simplified assumption, it is found that the microstructures have no effect on critical nucleation radius and their effect on the change in availability is underestimated.

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1. Introduction

Heterogeneous nucleation of saturated liquid on a superheated wall in pool boiling has important applications in many fields [1–3]. It is well-known from experiments that heating surface conditions, such as the wettability and surface roughness, play important roles on bubble nucleation and boiling heat transfer [4,5]. Experimental data show that nucleation boiling usually occurred earlier on hydrophobic surfaces with lower superheat required for onset of nucleation boiling (ONB) than hydrophilic surfaces [6,7]. This has been confirmed theoretically by a recent paper by Quan et al. [8], who have carried out an analysis on wettability effects on heterogeneous nucleation in a saturated liquid on a *smooth* superheated surface based on the change in Gibbs free energy function.

On the other hand, boiling experiments on heated surfaces with porous coating [9,10], mechanical fins or cavities [11,12] have shown that boiling heat transfer rates are also greatly enhanced. Recent experiments [13,14] showed that boiling incipience superheat could be significantly reduced, and the nucleate boiling heat transfer rate dramatically enhanced, through the fabrication of micro structures on the heated surfaces. Nam and Ju [15] performed experiments on bubble nucleation in pool boiling of water at an atmospheric pressure for different hydrophobic island sizes ranging from 10 μm to 100 μm on a *smooth* silicon substrate. They found that the measured superheat required for onset of nucleation boiling (ONB) in water was approximately 9 °C. Most recently, the interaction of wettability and microstructures on bubble nucleation has received a great deal of attention. In particular, Jo et al. [16] conducted pool boiling experiments on ONB of water on hydrophobic surfaces with microstructures having dot diameters in a wider range from 50 μm to 500 μm. The arithmetical average roughness and maximum peak-to-valley height of the heating surface was in nanometer scale. They obtained similar conclusions with those given by Nam and Ju [15] when the pattern size was less than 100 μm, but found that the required superheat for ONB sharply decreased as the pattern size exceeded 100 μm. However, the reasons for the differences in required superheat for ONB on surfaces with different roughness and wettabilities remain unclear.

Cole [17] formulated the problem on the influence of microstructures on heterogeneous ONB based on changes of Gibbs free energy and availability in a uniform temperature field. However, no detailed numerical results on the influence of micro particle size on ONB were obtained. Fletcher [18] investigated the size effect of spherical particle and surface properties upon the freezing of water on foreign nuclei based on the derivative of free energy analysis. The above analyses [17,18] were based on the simplified assumption that there was no temperature gradient in the liquid adjacent to the heated or cooled surfaces. As far as the authors are aware, no analysis has been carried out to study the interaction of microstructure and wettability effects on onset of boiling nucleation, taking into consideration the effect of the wall temperature

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Nomenclature

A	area (m^2)
d	distance between centers of the curvature of the microstructure and the bubble (μm)
$\tilde{d}$	dimensionless distance (d/r_b)
f_1, f_2	dimensionless functions
g	specific Gibbs free energy (J/kg)
G	Gibbs free energy (J)
h_{fg}	latent heat (J/kg)
k	temperature gradient (K/m)
m	mass (kg)
P	pressure (Pa)
q	heat flux (W/m^2)
r	spherical coordinate
r_b	bubble radius (μm)
R	surface curvature radius (μm)
$\tilde{R}$	dimensionless curvature radius (R/r_b)
R_g	gas constant (J/(kg K))
s	specific entropy (J/(kg K))
T	temperature (K)
u	specific internal energy (J/kg)
v	specific volume (m^3/kg)
V	volume (m^3)

Greek symbols

θ	contact angle (deg)
λ	thermal conductivity (W/(m K))
ρ	density (kg/m^3)
σ	surface tension (N/m)
φ	spherical coordinate
ψ	spherical coordinate
Ψ	availability (J)
$\tilde{\Psi}$	dimensionless availability

Subscripts

0	initial state
c	critical state
e	the case of $k = 0$
l	liquid
L	lower limit of integration
ONB	onset of nucleated boiling
s	solid
sat	saturated state
U	upper limit of integration
v	vapor
w	wall
+	convex structure
−	concave structure

gradient. It is relevant to point out that bubble critical radii in most of the previous analyses on homogeneous and heterogeneous nucleation were obtained by setting the change in Gibbs free energy equal to zero [8,17,18]. Most recently, we have carried out an analysis [19] to compare critical parameters for heterogeneous nucleation on a *smooth plane* surface with different wettabilities based on two different approaches: the changes in Gibbs function and in availability function, taking into consideration the wall temperature gradient.

In this paper, we will carry out an analysis to study the interaction of wettability and microstructures effects on heterogeneous nucleation with the wall temperature gradient in the superheated layer taken into consideration. Both the Gibbs free energy approach and the availability approach are carried out to obtain critical nucleation radius and nucleation heat flux. It is found that (i) nucleation occurs earlier on a concave surface than a convex surface or a plane surface at the same wettability and wall temperature, and (ii) the effect of microstructures greatly influences boiling heat transfer when the curvature radius of these microstructures is in the range of 5–100 times less than the bubble radius. Beyond this limit, the surface roughness effect is negligible and the wettability effect predominates.

2. Thermodynamic analyses

Consider a solid wall, having microscale roughness consisting of convex and concave microstructures with microscale curvature radius R, is submerged in a saturated liquid. If the surface is heated at a superheated temperature, a vapor embryo (with bubble radius r_b) will be formed within the superheated thermal layer adjacent to the heated surface with microstructures. Figs. 1 and 2 show that the vapor embryo forms on hydrophobic and hydrophilic surfaces respectively. It is assumed that the embryo bubble is of a truncated sphere, whose volume is influenced by the geometry and wettability (contact angle θ) of the microstructure. In this paper, we choose a 3-dimensional spherical coordinate system (r, φ, ψ) with its origin at the point O as the coordinate for the wall and the adjacent superheated liquid. The center of the bubble (O') is located at a distance d from the origin of the solid surface O. Thus, the differential element of bubble volume, the bubble volume (V) as well as surface areas of vapor–liquid and vapor–solid interfaces (A_{lv},A_{sv}) on

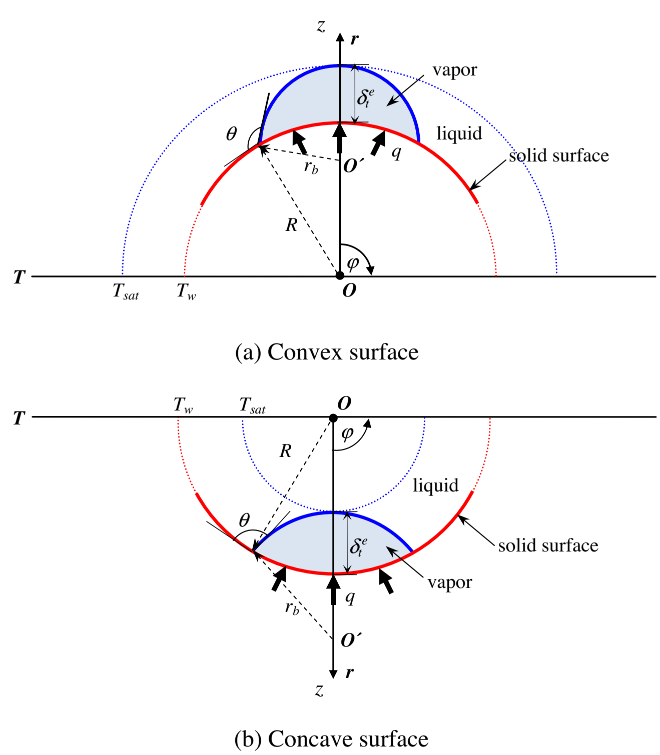

Fig. 1. Schematic drawing of an embryo bubble formed on hydrophobic surfaces ($\theta > 90°$): (a) convex surface and (b) concave surface.

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