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Heterogeneous bubble nucleation on ideally-smooth horizontal heated surface

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ABSTRACT

Our experiments and analyses of the bubble incipient on ideally-smooth, horizontal heated surface confirm the observed low superheat and the weak surface-wettability dependence. These are contrary to the previous heterogeneous nucleation predictions, so to clarify this difference and the experimental results not explained by previous nucleation theories we adapt a new model based the thermal boundary layer. The model includes the kinetic dynamics of the superheated liquid and the thermodynamic stability of the generated vapors. The fluid particle transfer rate is estimated with the Smoluchowski equation. Consequently, the incipient bubble nucleation on the ideally-smooth horizontal surface, with different wettability, is described and the predictions match the experiments fairly well.

1. Introduction

The early stages of nucleation theory, referred to as classic nucleation theory (CNT), are based on the Gibbs theory of new phase formation, ideal gas kinetics, and the energy barrier required for nucleus generation [1–5]. The energy barrier is mainly determined by the energy required for generating the new interface and the energy consumed by the phase change of the metastable initial phase to a stable state. In other way, kinetic nucleation theory (KNT) was also developed as a theoretical nucleation theory [6–12]. The main difference between CNT and KNT is how the model calculates the evaporation rate and condensation rate. In CNT, the nucleation rate is derived from the evaporation and condensation rates with an equilibrium distribution. In KNT, however, instead of using the equilibrium distribution, the evaporation and condensation fluxes and their corresponding transfer rates are calculated separately by considering kinetics and the potential field as a driving source. In recent studies, the rate of nucleation in the KNT model was characterized by the mean first passage time by solving the Smoluchowski equation [9–12]. According to previous nucleation theories, saturated water under atmospheric conditions could produce a newly generated bubble at ~300 °C.

The heterogeneous bubble nucleation occurs under transient or steady heating. In transient experiments the classical homogeneous high-superheat limit is observed, since the associated high heating rates prevent growth of vapor bubbles from the surface imperfections [13]. Steady-state results show reduced superheat, since (a) the surface is rarely smooth at the scale of the critical nucleus, and (b) the surface energy heterogeneities such as local hydrophobicity. Corty and Foust [14] and Bankoff [15] suggested that the widely accepted trapped-vapor theory, which states that cavities on commercial heating surfaces can trap vapors and then it act as nuclei, is the most likely theory for explaining the origin of a boiling bubble. In other words, if the surface cavity is larger than the critical nucleus, the cavity traps vapor and becoming nucleus for heterogeneous nucleation at low superheat. Furthermore, the local surface hydrophobicity also induces heterogeneous nucleation at a reduced superheat, since the nanobubbles existing on the hydrophobic sites become activated and form nucleus seed [16,17]. Qi and Klausner [18] hypothesized the occurrence of nanobubbles for heterogeneous nucleation and Nam and Ju [19] analyzed the incipience of nanobubbles at low superheat on Teflon patterned surface. However, the presence of the nanobubbles could be detached via degassing procedure [20]. Thus, there is a continuing debate on the mechanism of bubble nucleation on a hydrophobic surface without surface cavities at low superheat.

Recently, studies regarding bubble nucleation have entered a new phase with the introduction of advanced surface treatment techniques. The most interesting experimental result is heterogeneous boiling bubble nucleation at low superheats (with a superheat for bubble inception of only ~10 K under atmospheric

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Nomenclature

c	concentration of particles in one dimension (m^{-1})
D	diffusivity ($m^2\ s^{-1}$)
f	distribution function (–)
Gr	Grashof number (–)
g	acceleration of gravity [9.81 ($m\ s^{-2}$)]
h	latent heat ($J\ kg^{-1}$)
J	transfer rate ($s\ m^3$)$^{-1}$
k_B	Boltzmann constant ($J\ K^{-1}$)
L	the length from edge to center of heating surface (m)
n_B	number density of embryos (m^{-3})
P	pressure ($N\ m^{-2}$)
Pr	Prandtl number (–)
Q	survival probability (–)
R_{ideal}	ideal gas constant [8.314 ($J\ (K\ mol)^{-1}$)]
r	radius of nucleus (m)
s	entropy ($J\ (K\ kg)^{-1}$)
T	temperature (K)
t	time (s)
u	internal energy ($J\ kg^{-1}$)
$\vec{u}, \vec{v}$	x- and y-component velocities ($m\ s^{-1}$)
v	specific volume ($m^3\ kg^{-1}$)
x	horizontal position
y	vertical position

Greek symbols

β	volumetric thermal expansion coefficient (K^{-1})
θ	contact angle (°)
δ_t	thermal boundary layer (m)
Φ	dimensionless temperature (–)
φ	potential free energy ($J\ kg^{-1}$)
η	similarity variable (–)
μ	dynamic viscosity ($kg\ (m\ s)^{-1}$)
ρ	density ($kg\ m^{-3}$)
σ	surface tension (N/m)
τ	passage time (s kg)
υ	kinematic viscosity ($m^2\ s^{-1}$)
ψ	stream function (–)

Subscripts

av	average
B	domain B
lv	interface between liquid and vapor phase
sat	saturated state
top	the top of bubble
y	vertical coordinate
0	initial state
∞	bulk state

water-saturated conditions) on a smooth hydrophilic surface that does not have any microstructures to trap a vapor as the seed for the bubble nucleus [21–25]. Using microelectromechanical system (MEMS) techniques for sub-nanometer roughness heating surfaces, researchers have confirmed the phenomenon on a variety of surfaces. Furthermore, researchers report, heterogeneous nucleation at low superheat on hydrophilic nanostructured heated surface, with no microstructure or hydrophobicity to trap vapor for the bubble nucleation [25–28]. These results are contradictory to those predicted by the heterogeneous nucleation theories.

In this study, we explain recent observations of heterogeneous nucleation at reduced superheat on horizontal heated surface free from trapped vapor and under steady-state condition. These contrast the heterogeneous nucleation theories and to clarify this we use a model based on the thermal boundary layer. This combined with the kinetics and dynamics of the superheated liquid and the thermodynamic stability of the generated vapor, leads to prediction of heterogeneous nucleation condition in absence of micro cavities. This model can also be used for hydrophobic heating surfaces.

2. Experiments

To verify the reported nucleation phenomena without surface cavities and at low superheats, we conducted pool boiling experiments with distilled water under atmospheric saturated condition. The electric Joule heating method was employed, using a power supply. The main pool was an aluminum bath and was maintained at a saturated condition by a PID temperature controller. A thin-film (platinum) heater was embedded on one side of the silicon wafer, and smooth surfaces were fabricated on the other side of the wafer via micro-electromechanical system techniques. The complete platinum film heater was H-shaped due to the configuration of the electrode and the main heating components. The central region of the H-shape (10×10 mm) was the main heating area. Based on the measured resistance of heater and the correlation developed between resistance and wall temperature, the wall temperature was determined. Taking all instrument errors into account, the maximum uncertainty in the wall superheat is less than 1.2 °C over the measured range of the ONB [24,25].

To analyze the heterogeneous nucleation temperature for different wetting surfaces, we used two different wetting smooth surfaces: silicon and heptadecafluoro-1,1,2,2-tetrahydrodecyltrichlorosilane (HDFS) coated surface. The plain silicon wafer possesses a very smooth surface with sub-nanometer surface roughness. The HDFS was coated on silicon surface as a very thin layer using self-assembled monolayer (SAM) technique. As Fig. 1 shows, the plain silicon had a 72° static contact angle, while the static contact angle was 106° for the HDFS coated silicon surface.

To avoid the effect of trapped vapors on the surface cavity, the roughness of each surface should be smaller than the critical radius of the nucleus. The critical radius of the newly generated nucleus can be obtained by differentiating the energy barrier equation based on the Gibbs–Duhem equation (because there exists a maximum energy barrier for the nucleus at the critical condition), i.e.,

$$r_c = \frac{2\sigma_{lv}}{P_{sat}(T_l)\exp\left[\frac{\upsilon_l(P_l - P_{sat}(T_l))}{R_{ideal}T_l}\right] - P_l}. \quad (1)$$

According to the result, the critical radius of the nucleus is of the order of 1 μm (Fig. 2). However, the measured roughness of all surfaces were in the nanometer range, as shown in Table 1. This supports that the roughness of these surfaces could not trap vapor as the seed for the nucleation.

All experiments were conducted after degassing procedure for 2 h. With the system open to ambient air pressure through the reflux condenser, the degassed air was expelled while the steam condensed and returned back to the vessel. The tests were carried out by increasing the electrical input in small steps, until the ONB was reached.

Repeatable results for each surface were obtained up and including the ONB. The required superheats for the silicon and HDFS coated surface at the ONB were 10.7 and 4.4 K, respectively.