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The role of surface energy in heterogeneous bubble growth on ideal surface

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ABSTRACT

An analytical model for heterogeneous bubble growth during nucleate boiling with variable wettability on an ideal smooth surface has been developed. We analyzed the growth of bubbles in terms of the motion of the triple line, and three stages of bubble growth were identified based on the triple line motion. The transition points between these stages were modelled using a free-energy analysis and force-balance of the bubble growth system. We considered two bubble-growth pathways: one with a constant angle between the liquid–vapor interface and the surface, and one with a constant base (i.e., constant triple line), and the two paths are linked during a bubble growth. It is hypothesized that the transition from a regime to another is linked to the less expansive energy path. To confirm this, a bubble growth was experimentally observed on various different wettability surfaces, and the results of these experiments were compared with the analytical model. In general, a larger contact angle (i.e., a more hydrophobic surface) resulted in bubble growth with a larger triple line, and hence a larger base diameter and a larger departing bubble diameter.

1. Introduction

Boiling, as one of the efficient energy transfer mechanisms by a liquid-vapor phase change, has been widely researched and utilized in numerous thermal management areas: nuclear power plants, chip cooling, etc. In order to improve the boiling heat transfer efficiency of those thermal systems, recently, numerous fundamental understandings of boiling phenomena has been attempted and achieved. Various environmental conditions such the pressure, surface characteristics, and fluids of the boiling have been evaluated and discussed. In particular, the effect of surface wettability, which is one of the major surface features, on the bubble behavior during boiling process has been focused upon recently. The surface wettability of solids can be characterized from the contact angle of a liquid with the known surface tension, and used for an evaluation of the adhesion of bubbles or droplets on the surface. Because the dynamics of the three phases (i.e., liquid, vapor, and solid) are directly related to the wettability, the liquid-vapor interfacial behavior at the surface strongly depends on the wettability. Owing to its decisive effect of the wettability on the liquid-vapor dynamics, its physical role has been studied in-depth in the boiling and condensation heat transfer area [1–5].

Heterogeneous bubble growth is a basic mechanism of nucleate-boiling. As the bubble grows, part of the liquid-vapor interface that is in contact with the surface expands (1). This region is called a triple line. After a period of bubble growth, the expansion of the triple line ceases (2), and the bubble starts being deformed and elongated. After a greater period of the growth, the volume of the bubble grows and the buoyancy force of the bubble becomes significant and causes upward momentum to the bubble. When the upward buoyancy force exceeds the surface tension of the bubble with a surface, the bubble starts to leave from the surface. The bubble departs from the surface followed by the rapid shrinking (3) of the triple line. The three bubble stages can be identified in terms of the motion of the triple line (expand, stay, shrink), and these stages and the triple motions are affected by a number of factors, including the wall superheat, pressure, and surface conditions. In particular, since the surface wettability strongly dominates the dynamics of the triple line during the heterogeneous bubble growth, the three stage of bubble growth can be governed by the wettability of the boiling surface.

The effects of the surface wettability on the bubble dynamics have been widely studied, and the performance of the boiling heat

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Nomenclature

A	area [m^2]
c_p	specific heat [J/K]
E	energy [J]
F	force [N]
H	latent heat [J/K kg]
h	height [m]
k	volume increment
L	length [m]
r	bubble radius [m]
T	temperature [K]
t	time [s]
V	volume [m^3]

Greek symbols

α	thermal diffusivity [m^2/s]
θ_c	contact angle of a water droplet on the surface [°]
$\theta_{1,2}$	contact angle between the liquid–vapor interface and the surface [°]
ρ	density [kg/m^3]
σ	surface tension [N/m]

Subscripts

a, b	path A, path B
base	base
l	liquid
M	mechanical
S	surficial
s	solid
sat	saturation
v	vapor
w	wall
1	state 1 (initial state)
2	state 2 (later state)

Dimensionless numbers

Ja	Jakob number $\left(\frac{(T_w - T_{sat})\rho_l C_{p,l}}{\rho_v H_{lv}}\right)$

transfer has also been investigated [6–15]. Because the size of the departing bubble and the release frequency are directly related to the boiling heat transfer rate, a significant amount of research has focused on the physical relationship between the two parameters (i.e., the departing bubble size and release frequency), as well as the surface wetting conditions [16–18]. The surface wettability can be analyzed in detail by considering the surface energy. The sum of the surface energy (liquid-vapor-solid) determines the contact angle of the wetting system (wettability). In case of boiling, as the surface energy becomes small (i.e., a more hydrophobic surface), the departing bubble diameter becomes large. Since a surface with a large contact angle has a large surface tension force, the liquid-vapor interface tends to adhere to the surface, resulting in the larger departing bubble. At a surface with a contact angle of greater than 90°, the triple line L becomes large, leading to a large surface energy [6–8]. It has generally been reported that a larger contact angle leads to a larger departing bubble; however, Phan et al. [9–12] reported that a hydrophilic surface can result in a larger departing bubble than a hydrophobic surface in sub-cooled conditions. Because bubble growth is typically described by dynamic and complex, rather than static, physics, some controversy exists in the related literature. Furthermore, these experimental observations and their correlating bubble dynamics are largely and inevitably dependent on empiricism to quantify the data.

Recently, various numerical approaches have contributed to bubble growth during a nucleate boiling, and only a few studies have reflected the surface wettability effect. Dhir et al. [19] simulated the dynamics of growth and departure of single and multiple merging bubbles and the associated heat transfer. A finite difference scheme with a level set method has been adopted, and the effects of surface wettability on the bubble diameter at departure and growth period have been quantified. Mukherjee and Kandlikar [14], as well as Hazi and Markus [15], studied bubble growth with various contact angles using numerical simulations. Mukherjee and Kandlikar [14] calculated the bubble growth using both static and dynamic contact-angle models, solving the complete Navier–Stokes equations and using the level-set technique to describe the liquid-vapor interface. Small differences in the bubble growth and boiling heat transfer have been reported, depending on whether a static or dynamic contact-angle model is used. Kunugi and Ose [20] conducted a Direct Numerical Simulation (DNS) of boiling phenomena in various subcooled conditions and surface wettability environments, and shows very good agreement with the experimental results.

Herein, we investigate a fundamental role of the surface wettability on heterogeneous bubble growth on a smooth surface using an energy-force analysis. The effects of the surface and mechanical energies of the bubble were modeled analytically. We considered two different growth paths of the bubble; the bubble size at the transition between the three stages of growth was calculated from the difference in energy of the two growth pathways. The free energy of the bubble growth depends on the surface wettability, and this can be used to predict the bubble dynamics for the surface conditions. Although this theoretical work has rough physical and analytical assumption and calculation, it covers the fundamental physics of wetting-associated on the bubble growth. The above analysis is quite lower in cost and simpler than a numerical simulation, and logically and fundamentally supports the method well. To confirm the analysis, experimental observations of nucleate boiling on different surfaces employed self-assembled monolayers (SAMs) deposited on a polished silicon wafer, and shows good agreement with the above analysis. Lower surface energies (i.e., more hydrophobic surfaces) had larger departing bubbles, as observed in both the calculations and experiments.

2. Experiments

In this study, pool-boiling experiments have been carried out under saturated deionized (DI) water and atmospheric pressure conditions. To obtain the different contact angles with a negligible surface roughness (a few nanometer scale), several SAMs were deposited on a polished silicon wafer. The bubble growth during a nucleate pool boiling was visualized using a high-speed camera.

2.1. Sample preparation

The wettability of the samples used for the boiling experiments was controlled using different SAMs deposited on a polished silicon wafer. Four different surfaces were prepared. The first was a bare polished silicon wafer, the second was a SAM formed using a bromo-terminated monolayer (BROM), the third was coated with