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Wetting characteristic of bubble on micro-pillar structured surface under a water pool

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ABSTRACT

In this study, the contact angle of air bubbles on a micro-structured surface under a water pool is experimentally investigated. A previous study "Kang and Jacobi, Equilibrium Contact Angles of Liquids on Ideal Rough Surfaces, *Langmuir* (2011)" adopted the work of adhesion as the additional work of the process of droplet contact on a textured surface, and it explained the reason for failure of the classical theoretical model (Wenzel equation) in real wetting tests. We extended the above concept to bubble interaction with the textured surface. First, the bubble contact angles on the textured surface were modeled based on the concept of the work of adhesion in the free energy calculation. Second, the contact angle of air bubbles was measured on the bottom of test surfaces under a water pool. The test-section surfaces have micro-pillars with a size of 5–40 µm prepared by the microelectromechanical systems (MEMS) technique. The bubble contact angles were compared with both the modeled bubble shape and classical prediction (Wenzel & Cassie–Baxter equations). In addition, detail wetting features which shows wetting transition and critical wetting behavior of bubble were discussed.

1. Introduction

Since the wetting of droplets and bubbles on a solid surface plays dominant role in various liquid-vapor-solid physical systems, the wetting characteristics have attracted tremendous interest in not only fundamental research but also many industrial applications such as oil recovery, lubrication, liquid coating, printing, and spray quenching. The understanding of droplet wetting also provides insight into the heat transfer of the liquid-vapor phase change in cases of a droplet on a heating/cooling surface, and the cooling performance of condensation and spray cooling have been directly attributed to the wetting features [1–6]. In other hand, the wetting feature with bubble also plays an important role in bubble-wall interaction processes (e.g., material flotation, fluidized bed, and particle sedimentation). For instance, nucleate boiling, which is applied in various energy conversion process (e.g., nuclear power plants, electronic cooling devices, and air-conditioning), strongly depends on the bubble behavior [7–15].

In general, the wetting of droplets and bubbles on a solid surface can be characterized by the contact angle (θ), which indicates the surface-energy state of the rigid solid. The contact angle at the triple line, where the three phase (liquid, gas and solid) coexist, results from the balance of the surface tension between the two phases (Young's relation) on an ideal smooth surface as follows [16].:

$$\sigma_{sg} - \sigma_{sl} = \sigma_{lg}\cos\theta. \tag{1}$$

Recently, numerous textured surfaces have been introduced to modify the wetting physics (contact angle). For textured surfaces with nano- and micro-scale morphologies, droplets meet two types of wetting states: the Wenzel state and Cassie–Baxter state, which correspond to a fully wetted state and partially wetted state, respectively [17,18]. Such textured surfaces can yield extreme wetting conditions such as superhydrophilic ($\theta < 10^\circ$) and superhydrophobic ($\theta > 160^\circ$). For a long time, these contact angles on various textured surfaces have been evaluated based on the Wenzel and Cassie–Baxter model. However, numerous inconsistencies with this classical model have been reported [19–22]. For example, the Wenzel model frequently failed to explain the droplet contact angle on textured surfaces when the intrinsic contact angle, which is the contact angle without roughened condition, is less than 90°. Recently, Kang and Jacobi [23] proposed a modification to the classical model that introduces the work of adhesion between the liquid droplet and surface, and it explains successfully the droplet contact angles on textured surfaces.

Compared with the droplet wetting analysis, wetting feature with bubble has been studied less extensively. Because it was considered that the basic principle of determining the wetting shape and dynamics in terms of surface energy analysis are not different regardless of the

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Nomenclature

V	volume [m^3]
A	area [m^2]
w	work of adhesion [N/m]
r	roughness [–]
F	Helmholtz Free Energy [J]
d	diameter [m]
g	gap [m]
h	height [m]

Greek symbols

ρ	density [kg/m^3]
σ	surface tension [N/m]
θ	contact angle [°]
ϕ	solid fraction [–]

Subscripts

l	liquid
g	gas
s	solid
Y	Young's relation
D	droplet
B	bubble

phases (droplet and bubble), relatively less test and discussion of the bubble-wall interaction have been performed. However, it can be applicable only if the wetting process follows the quasi-equilibrium process, which is a relatively slow interaction. In the bubble-wall contacting condition, the surrounding fluid which has relatively much high density and viscosity than drop-air condition can have an influence on the adhesion process or dynamic wetting process of bubble-wall interaction. According to the author's literature survey and understand, only a couple of studies about the bubble contact angle varying the bubble size and related properties has been reported. [24,25]. In general, bubble contact angle (θ_B) on a flat surface can be estimated by Young's equations, and it can be measured by the captive bubble method (sessile bubble method) [26], that a bubble of air is injected on downward-facing solid surface, instead of placing a drop on the solid as in the case of the sessile drop method [27–29].

It was reported that there are different fluctuation in contact angle between droplet bubble on rough surfaces, depending on the captive bubble method and sessile drop method. [30]. Additionally, bubble size and contact angle also have an influence on the air bubble/aqueous phase/paraffin system, and it was proposed to modify the Young's equations with the line-tension to predict the dynamic contact angle (See Eq. (2)) [31]. This modified equation is applicable to homogeneous, rigid, flat, horizontal, and smooth solid surfaces, and it is expressed as follows:

$$\sigma_{sg}-\sigma_{sl}=\sigma_{lg}\cos\theta+\frac{\sigma_{slg}}{r}. \tag{2}$$

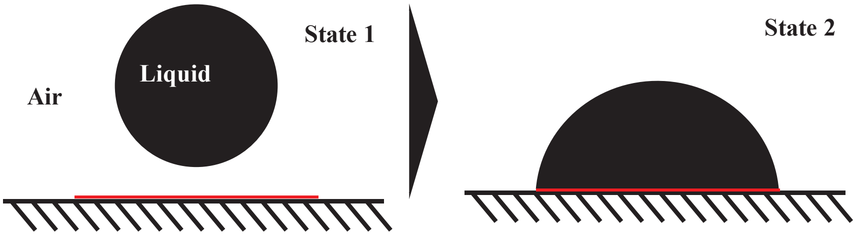
where σ_{slg} is the line tension: the excess free energy in the region of the triple interface. Drelich et al. also showed that the surface roughness and heterogeneity strongly influence the dynamic contact angle and bubble size, particularly the receding contact angle [32]. As mentioned above, several researchers have studied the fundamentals of wetting features (static/dynamic) for various surface conditions and fluidic environmental conditions.

In this study, in order to evaluate the bubble contact angle on designed micro-pillar structured surface in terms of wetting transition and prediction model applicability, simple bubble captive method of experimental work has been performed. For the experiments, textured surfaces were prepared by the microelectromechanical system (MEMS) technique and a coating method. The air bubble contact angles were measured by the captive bubble method and the results were compared with the modified Kang & Jacobi work for bubble-wall interaction. This study on bubble interfacial phenomena may give a fundamental picture of the bubble–wall interaction and the relevant applications.

2. Modeling of bubble contact angle

We are going to derive the bubble contact angle on textured surface based on the Kang and Jacobi's work [23], which is briefly reviewed in

(a) Droplet wetting



(b) Bubble de-wetting

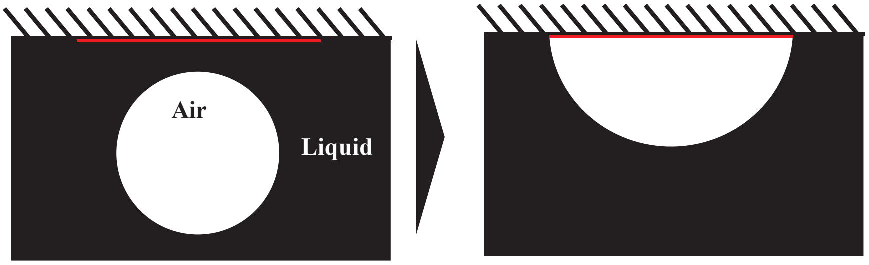


Fig. 1. Modeling of wetting by (a) a droplet and (b) a bubble.