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Investigation of nanofluid bubble characteristics under non-equilibrium conditions

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ABSTRACT

We report experimental and theoretical investigations of the bubble characteristics during the oscillatory growth period for several nanofluids. The nanoparticles were found to affect liquid–gas and solid surface tensions, which modulated the bubble contact angle, radius of triple line, bubble volume and the dynamics of bubble growth. To increase the accuracy of the Young–Laplace equation predictions during the bubble growth in the oscillatory period, a new method multi-section bubble (MSB) approach was developed. In this method, the bubble was divided into n sections (i.e., $n = 1{:}N$) and the Young–Laplace equation was solved for each section individually. As N increases, within each section the effects of inertia force and viscosity become reduced comparing to that of the liquid-gas surface tension. Unlike the conventional Young–Laplace approach (i.e., $N = 1$), the new approach is able to predict the bubble characteristics reliably in the following cases: (a) the oscillatory period when bubble is fluctuating; (b) the departure period when bubble is stretched upward, right before departure; and (c) the high shear stress condition when gas velocity is relatively high.

1. Introduction

The Young–Laplace equation has been used to predict the droplet shape and contact angle on horizontal [1] and inclined substrates. The Young–Laplace equation is also able to predict the bubble shape when both phases are in equilibrium at the interface and the effect of shear stress is negligible. However, the applicability of the Young–Laplace equation becomes invalid when: (a) the bubble is in the departure period [2], (b) the shear stress is relatively high and (c) the bubble is fluctuating [3]. One application where these conditions may occur is during boiling of fluids on hot surfaces, which has received a strong research interest with the invention of nanofluids. To address these challenges, one possible avenue would be to develop and solve a set of equations containing the additional effects of high shear and inertial forces. Here we propose an alternative solution based on using Young–Laplace equations over different sections of the bubble, in order to increase the accuracy of the prediction of bubble shape and enable the fast determination of important bubble characteristics such as volume and contact angle. The technique is applied to study the bubble characteristics inside nanofluids during the oscillatory period.

It has been reported that nanoparticles are able to modify the thermal conductivity [4], viscosity [5], liquid–gas [6], and solid surface tensions, $\sigma_{sg} - \sigma_{sl}$, [7], and possibly the gas–liquid–solid interactions at the triple line. The variation of liquid–gas and solid surface tensions would affect the force balance and consequently the dynamics of the triple line, which has a significant role on the bubble growth [3,8], and boiling heat transfer coefficient and critical heat flux [9,10]. The schematics of liquid–gas and solid surface tensions at the triple line are exhibited in Fig. 1, for bubbles and droplets. The dynamics of triple line on a substrate [8,11] or a hot plate [12–15], also depend on the nature of the gas and liquid phases, the characteristics of the solid surface [7,16,17], and the receding and advancing contact angles [18].

Nanofluids have been also found to induce different spreading and thinning (layering) behavior at the triple region compared to the pure liquids. The nanoparticles were observed to spread stepwise inside the triple region on a smooth hydrophilic glass surface. The number of layers of nanoparticles decreases in a stepwise pattern as nanoparticles gets closer to the edge of triple line. Apparently the layering phenomenon of the nanoparticles at the triple region depends on many factors such as concentration

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Nomenclature

g	acceleration of gravity [m/s^2]
R_o	radius of curvature at apex [m]
R_1,R_2	radius of curvature [m]
r_d	radius of contact line [m]
V	bubble volume [m^3]
Q_n	nominal gas flow rate [ml/min]
u	gas velocity [m/s]

Greek Symbols

δ	height of apex [m]
θ_o	bubble contact angle [Deg.]
θ_e	droplet contact angle [Deg.]
θ_s	asymptotic contact angle [Deg.]
ρ_l	liquid density [kg/m^3]
ρ_g	gas density [kg/m^3]
σ_{lg}	liquid–gas surface tension [N/m]
σ_{sg}	solid–gas surface tension [N/m]
σ_{sl}	solid–liquid surface tension [N/m]
$\sigma_{lg\ n}$	liquid–gas surface tension of nanofluids [N/m]

and characteristics of nanoparticles, nanoparticle charge, solid–liquid–gas materials and film size [19,20]. It has been shown theoretically that particles can spread the triple line to a distance of 20–50 times of the particle diameter through a structural disjoining pressure by self-ordering of particles in a confined wedge. However, the structural disjoining force only becomes significant at relatively high particle concentrations, i.e., over 20 vol.% [21].

In this paper we report the effects of different nanoparticles on the dynamics of triple line and bubble growth. Using a new multi section bubble (MSB) method presented here, the Young–Laplace equation was solved to predict the bubble shape and was compared with experimental data for bubble growth inside water, gold, silver and alumina nanofluids throughout the bubble formation period including the oscillatory period. The paper is organized as the following: Section 2 presents the new method for bubble shape prediction; Section 3 reports the experimental setup; Section 4 discusses the results and comparison between the model prediction and the experiment, and the final conclusions are summarized in Section 5 lines.

2. Prediction of the profile of bubble shape

Mathematically, the Young–Laplace equation can be interpreted as a mechanical equilibrium condition between two

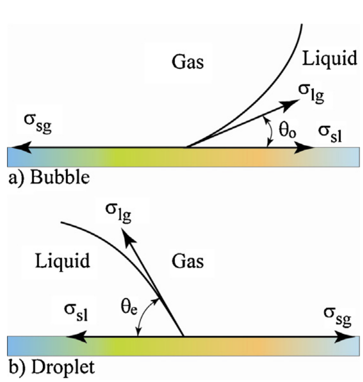

Fig. 1. Schematic of forces at the bubble/droplet triple.

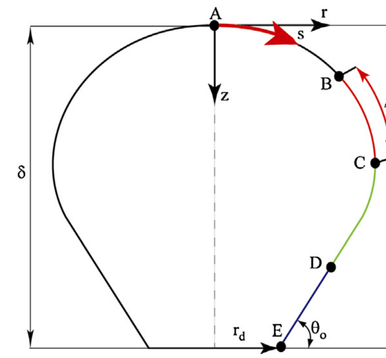

Fig. 2. Illustration of schematic of the bubble shape where bubble is divided into several.

fluids separated by an interface. It gives the pressure difference across the interface as a function of the product of the curvature multiplied by the gas–liquid surface tension

$$\Delta p = (\frac{1}{R_1} + \frac{1}{R_2})\sigma_{lg} \tag{1}$$

where R_1 and R_2 are the radii of the interface curvature, i.e., R_1 is the radius of curvature, describing the latitude as it rotates and R_2 is the radius of curvature in a vertical section of the bubble describing the longitude as it rotates. The centers of R_1 and R_2 are on the same line, vertical to the interface, but different location. Δp is the pressure difference between gas, p_g, and liquid, p_l (see Fig. 2). For bubbles, the gas pressure as a function of z is given by

$$p_g(z) = \frac{2\sigma_{lg}}{R_o} + p_o + \rho_g g z \tag{2}$$

The first term on the right hand side is the pressure difference at the bubble apex, p_o is liquid pressure at the apex, and last term is the hydrostatic gas pressure. Similarly the liquid pressure can be written as

$$p_l(z) = p_o + \rho_l g z \tag{3}$$

The radii of curvature are

$$R_1 = \frac{ds}{d\theta} \text{and} R_2 = \frac{r}{\sin\theta} \tag{4}$$

where θ, r, and s are, respectively, the bubble contact angle, the radius of the bubble and the length of bubble perimeter at the location of z (see Fig. 2). R_o is radius of curvature at apex. Substituting Eqs. (2)–(4) into Eq. (1), the Young–Laplace equation for bubbles becomes

$$\frac{d\theta}{ds} = \frac{2}{R_o} - \frac{gz}{\sigma_{lg}}(\rho_l - \rho_g) - \frac{\sin\theta}{r} \tag{5}$$

Similarly, the Young–Laplace equation for droplets can be written as

$$\frac{d\theta}{ds} = \frac{2}{R_o} + \frac{gz}{\sigma_{lg}}(\rho_l - \rho_g) - \frac{\sin\theta}{r} \tag{6}$$

In case of nanofluids, the liquid–gas surface tension, σ_{lg}, has to change to the liquid–gas surface tension of nanofluids, $\sigma_{lg\,n}$. The Young–Laplace equation can be solved [1,22–30], with following system of ordinary differential equations for axisymmetric