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Historical perspective

Modification of the Young–Laplace equation and prediction of bubble interface in the presence of nanoparticles

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ABSTRACT

Bubbles are fundamental to our daily life and have wide applications such as in the chemical and petrochemical industry, pharmaceutical engineering, mineral processing and colloids engineering. This paper reviews the existing theoretical and experimental bubble studies, with a special focus on the dynamics of triple line and the influence of nanoparticles on the bubble growth and departure process. Nanoparticles are found to influence significantly the effective interfacial properties and the dynamics of triple line, whose effects are dependent on the particle morphology and their interaction with the substrate. While the Young–Laplace equation is widely applied to predict the bubble shape, its application is limited under highly non-equilibrium conditions. Using gold nanoparticle as an example, new experimental study is conducted to reveal the particle concentration influence on the behaviour of triple line and bubble dynamics. A new method is developed to predict the bubble shape when the interfacial equilibrium conditions cannot be met, such as during the oscillation period. The method is used to calculate the pressure difference between the gas and liquid phases, which is shown to oscillate across the liquid–gas interface and is responsible for the interface fluctuation. The comparison of the theoretical study with the experimental data shows a very good agreement, which suggests its potential application to predict bubble shape during non-equilibrium conditions.

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1. Introduction

Nanofluids, functional nanoparticle dispersions, have been recently employed to enhance thermal management of miniaturized devices, ink jet printing, automobile industries, chemical and power plants, pharmaceutical industries and biomedical engineering. In many studies, nanoparticles have been observed to be able to modify thermal conductivity [1,2], viscosity [2,3], liquid–gas [4–6] and solid surface tensions [7] of the base fluid. The modification of the effective thermophysical properties influences the pressure drop and heat transfer coefficient in macro/microchannels [2]. The modification of liquid–gas and solid surface tensions would change the force balance at the triple line and

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consequently affect its dynamic behavior, [7,8] including the radius of triple line [9] and the bubble contact angle [5,10], which has significant effects on the bubble growth and departure process [11–16], as well as the boiling heat transfer [6,17–24].

This paper reviews the existing experimental, analytical and numerical approaches, associated with the behavior of triple line and the dynamics of bubble growth and departure process, with and without the presence of nanoparticles. In addition, the Young–Laplace equation is modified to increase the accuracy of the bubble shape prediction when the equilibrium between gas and liquid is relatively weak, i.e., during the bubble fluctuation period when the shear stress is relatively high or in the departure period where the bubble is stretched upwards. A new method is developed to calculate the pressure difference between gas and liquid phases which is observed to oscillate across the liquid–gas interface, along the perimeter of bubble. In addition, the effects of gold nanoparticles on the liquid–gas surface tension, the dynamics of triple line, and the bubble growth and departure process are investigated experimentally.

2. Overview of the behaviour of triple line

The liquid–gas, σ_{lg}, solid-liquid, σ_{sl}, and solid-gas, σ_{sg} surface tensions are the major effective forces at the triple line, as shown schematically in Fig. 1 (a, c) for bubbles and droplets respectively. The Young equation, $\sigma_{lg}\cos\theta_e = \sigma_{sg} - \sigma_{sl}$, demonstrates the force balance at the triple line traditionally, where θ_e is the equilibrium contact angle. The Young equation is associated with several restrictions and has never been experimentally verified for axisymmetric droplets. Its application is limited to the situations where the substrate is ideal [25,26] and the contact angle is size independent [27,28]. The Young equation cannot be applied directly except for long droplets [27]. Because of contact angle, the left side of the Young equation is size dependent, while the right side of the equation contains physical properties which make the equation inconsistent. The force balance between liquid–gas and solid surface tensions has a significant role on the behavior of triple line and consequently the interfacial shapes of bubbles and droplets.

The liquid–gas surface tension can be found for most of materials however the solid-liquid and solid-gas surface tensions are not easily available. Several independent approaches have been employed to calculate the solid surface tensions [26,29], such as Berthelot's combining rule [30], $\sigma_{sl} = (\sqrt{\sigma_{lg}} - \sqrt{\sigma_{sg}})^2$, the modified Berthelot's rule [31], $\sigma_{sl} = \sigma_{lg} + \sigma_{sg} - 2\sqrt{\sigma_{lg}\sigma_{sg}}\exp{-\beta(\sigma_{lg} - \sigma_{sg})^2}$, the alternative formulation [32,33], $\sigma_{sl} = \sigma_{lg} + \sigma_{sg} - 2\sqrt{\sigma_{sg}\sigma_{lg}}(1 - \beta_o(\sigma_{lg} - \sigma_{sg})^2)$, and the equation of state formulation [34,35], $\sigma_{sl} = \frac{(\sqrt{\sigma_{lg}} - \sqrt{\sigma_{sg}})^2}{1 - 0.015\sqrt{\sigma_{lg}\sigma_{sg}}}$, where $\beta = 0.000115(m^2/mJ)^2$ and $\beta_o = 0.0001057(m^2/mJ)^2$.

The given correlations have been compared against each other for some materials and the relative agreement has been reported [29]. The solid surface tensions has a key impact on the behavior of triple line while the liquid–gas surface tension is supposed to be fixed in a certain range, such as the applications of nanofluids in printing conductive wires. The radius of triple line was observed to expand towards the gas phase as the solid surface tensions increased [14].

In general, the characteristics of the substrate, the force balance at the triple line (see Fig. 1a, c) and gravity are the main factors influencing the behavior of triple line of bubbles and droplets. The behavior of triple line can be studied using either the droplet or the bubble method. In the case of droplets, the gravity has a positive impact on the spreading of the triple line, in favour of the reduction of contact angle. As an evidence of that, the behavior of triple line would change tremendously with varying droplet volumes [27,28]. The droplet contact angle can not be a unique criterion to measure the wettability, or the effects of nanoparticles. Similarly it has been clearly observed that the droplet contact angle varies under different gravitational accelerations based on the parabolic flight experiments [36] and drop tower tests [37]. It has been observed

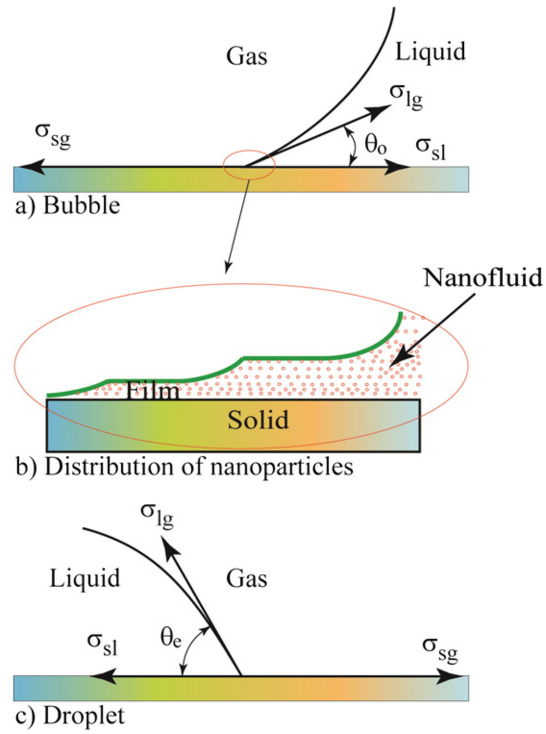

Fig. 1. Schematic of forces at the bubble/droplet triple line.

that droplet contact angle increases as the effect of gravity decreases. As the gravitational acceleration decreases to zero, the droplet shape gradually changes to a spherical cap. The droplet contact angle under zero gravity has been defined as the asymptotic contact angle, θ_s, [7,27]. The asymptotic contact angle is only dependent on the interactions between gas, liquid and solid at the triple line, and it is a unique criterion to measure the surface wettability or the effects of nanoparticles on surface wettability. The asymptotic contact angle can be obtained experimentally and theoretically. Recently, a new analytical expression has been developed, $r_d \sin\theta_e = \left[\frac{3V}{\pi(2+\cos\theta_s)(1-\cos\theta_s)^2}\right]^{1/3}\sin^2\theta_s$, to calculate the asymptotic contact angle, θ_s, [7,27], where r_d and V are the radius of the triple line and the droplet volume respectively. Using the asymptotic contact angle, the solid surface tensions can be calculated by having liquid–gas surface tension and the modified form of the Young equation, $\sigma_{lg}\cos\theta_s = \sigma_{sg} - \sigma_{sl}$ [7], which describes the force balance between liquid–gas and solid surface tensions under zero gravity condition.

Another approach has been employed to explain the variation of droplet contact angle with volume, based on the concept of line tension, which has a significant role on adjusting the effect of droplet size on contact angle. In this method, the Young-equation has been modified as, $\frac{\sigma}{r_d} + \sigma_{lg}\cos\theta_e = \sigma_{sg} - \sigma_{sl}$, by considering the effect of line tension, σ. The value of line tension has been obtained experimentally [26,38] and theoretically [39,40]. The line tension operates to expand the length of triple line when it is negative and vice versa [38]. Most probably, the line tension would be zero in no-gravity condition, since the droplet contact angle, liquid–gas and solid surface tensions are constant while the radius of triple line would change by volume. It has been reported that (a) the line tension decreases as the wettability increases and likely vanishes at supper wetting conditions [41], (b) the line tension is a function of liquid material [41–44], and (c) the determination of line tension is still involved with large uncertainties, including both the magnitude and the sign of the line tension [26,45]. The accurate measurement of line tension is difficult due to a number of issues, including (a) the value of line tension is small, (b) the lack of accurate measurement,