Bubble growth inside an evaporating liquid droplet introduced in an immiscible superheated liquid

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ABSTRACT

A numerical bubble growth model for two phase droplets in an immiscible superheated liquid is developed by solving the mass and energy conservation equations. The model is applicable for concentric two-phase droplets (where the bubble is completely surrounded by the volatile liquid) like those seen during evaporation of refrigerants suspended in water. The effect of pressure driven growth in the initial phases of bubble growth is shown to be minimal and is therefore ignored to simplify the model. While previous works assumed that the droplet is initially uniformly superheated, the current model assumes a more accurate temperature profile obtained by solving the radial heat diffusion equation in the droplet and surrounding liquid. The model is validated by measuring bubble growth rate within an FC-72 droplet introduced in a water bath and it is seen that the results are in close agreement with the model predictions. Experimental results from various cases in literature are also found to be well represented by the model. The effect of the liquid superheat and initial bubble diameter on bubble growth rate is also studied. Finally, a parametric study on the effect of droplet and bulk liquid properties on bubble growth rate is conducted to highlight the relative importance of the thermal conductivity and thermal mass ratios of the two liquids.

1. Introduction

The motivation behind studying bubble growth rates in a two-phase droplet is its application in direct contact evaporators. In surface type heat exchangers, such as the commonly used shell and tube type, heat is transferred through a metallic barrier present between the two liquids. The mere presence of this barrier introduces a number of issues. The solid barrier lowers the heat transfer rate, and is exposed to fouling, corrosion, and thermal stresses [1]. Some of these issues may be overcome with the use of specialized materials or additives, but their use further raises the material costs associated with these heat exchangers. The operational cost for these systems is also high due to continuous maintenance and the associated fouling and corrosion [1]. Direct contact heat exchangers eliminate the need for a metallic barrier by bringing the two fluid streams into direct physical contact. This increases the associated heat transfer coefficients and reduces material and operational costs [1]. These systems have broad

industrial applications such as water desalination, solar energy applications, and power production from low-grade energy resources such as geothermal. Heat transfer in direct contact evaporation systems have been studied in both single droplet and spray column configurations. However, studies involving visualization of bubble nucleation and growth in direct contact systems have been scarce. Some significant analytical studies have also been carried out that predict heat transfer and bubble growth rate when a single droplet is introduced into an immiscible superheated bulk liquid.

Multiple theoretical and experimental studies on direct contact heat transfer have been carried out by Mahood's group [1–8]. Experimental studies were carried out with single *n*-pentane drops in flowing water [7]. Video analysis was used to yield instantaneous bubble growth, rise velocity, and heat transfer coefficients. The evaporation is divided into four regions with the behavior of a spherical droplet, spheroidal bubble-droplet, large spheroidal bubble, and a spherical cap bubble. In another study, an analytical bubble growth model was derived [8]. They include both convective and conductive heat transfer and are able to derive a closed form solution for the Nusselt number as a function of the Prandtl and Reynolds numbers. In another experimental study, the average volumetric heat transfer coefficient in a spray column direct contact evaporator was investigated with *n*-pentane and water. From

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these results, it was concluded that a smaller initial droplet size yields higher heat transfer coefficients. They varied the sparger configuration but did not see a notable impact. The performance of direct contact condensers have additionally been studied by this group [2,4].

During evaporation of the liquid droplet in a superheated immiscible liquid bath, the position of the vapor bubble relative to the liquid-liquid interface determines the rate of evaporation of the droplet. Johnson and Sadhal [9] and Mori [10] studied engulfment of a bubble by a dispersed phase liquid in an immiscible liquid medium and proposed a spreading coefficient, S, that can be used to predict bubble engulfment. The spreading coefficient is given by:

$$S_i = \sigma_{jk} - (\sigma_{ij} + \sigma_{ik}) \quad (i \neq j \neq k = A, B, G) \quad (1)$$

where A, B, and G denote the dispersed, continuous, and gas phases respectively. Based on the spreading coefficient, a two-phase droplet can take one of four configurations, as shown in Fig. 1. For water-FC-72-gas combination the spreading coefficients are $S_A > 0$, $S_B < 0$ and $S_G < 0$ and therefore the gas is encapsulated by the FC-72 liquid [11]. Avedisian and Andres [12] studied the nucleation characteristics in hydrocarbon-water emulsions and suggested that a bubble nucleates at the liquid-liquid interface and remains within the hydrocarbon phase as the bubble grows.

The bubble growth models in literature can be classified into two main categories based on the degree of engulfment of the vapor bubble by the dispersed phase liquid: (i) models that assume the nucleating bubble is partially covered by the dispersed liquid while the rest of the bubble is in direct contact with the bulk liquid, and (ii) models that consider the bubble to be completely engulfed by the evaporating liquid.

A seminal work on heat transfer in single droplet systems was conducted by Sideman and Taitel [13]. The authors considered that a segment of the bubble is exposed to the bulk liquid and the evaporating liquid covers the rest, forming a 'crescent' shape around the bubble. The net heat transfer coefficient expressed in terms of Nusselt number, Nu, was found to be proportional to the initial volume of the droplet, independent of liquid superheat, and was expressed as a function of the bubble opening angle, β, and Peclet number, Pe:

$$Nu = [(3\cos\beta - cos^3\beta + 2)/\pi]^{0.5} Pe^{0.5} \quad (2)$$

As the bubble grows, the volatile liquid shell becomes thinner and reduces the conduction resistance across the shell. However, the model predicts very high heat transfer coefficients during initial phases of bubble growth due to large liquid-liquid interface area. Tochitani et al. [14,15] proposed a rigid sphere model where the liquid-liquid interface area was assumed to remain constant up to a vaporization ratio of 10% and reduced upon further evaporation. Raina and Grover [16] introduced the effect of viscous shear on the spreading of the dispersed phase over the bubble interface.
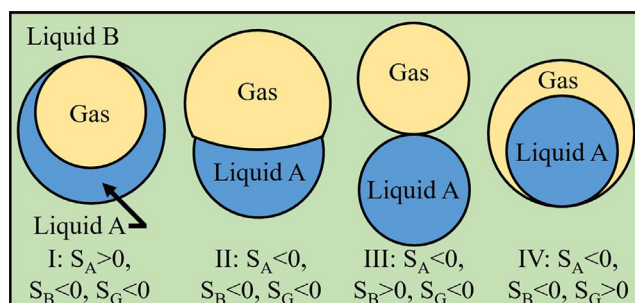

Fig. 1. Possible configuration of liquid-gas two phase bubbles.

Contrary to Sideman and Taitel [13], a regression analysis carried out by Battya et al. [17] showed that the Nusselt number is influenced by the temperature difference through Jakob number, Ja:

$$Nu = 0.64 Pe^{0.5} Ja^{-0.35} \quad (3)$$

Haustein et al. [18] studied bubble growth in a two-phase droplet at high superheats through sudden depressurization. They proposed a simplified model of bubble growth where a liquid shell is present around the bubble until 30% evaporation, after which the shell is assumed to rupture. Their droplet configuration is similar to that described by Sideman and Taitel [13]. They identified three characteristic times during bubble growth relating conduction and convection heat transfer and the shell rupture.

Avedisian and Suresh [19] developed a numerical model to predict bubble growth rate when a bubble nucleated in a superheated droplet in a superheated bulk liquid. The initial temperature of both liquids is assumed to be the same. The continuity, momentum, and energy conservation equations were solved to obtain the bubble growth rates. Since the problem has a moving boundary, the equations were nondimensionalized using a technique known as Landau immobilization. It was seen that until the thermal boundary layer at the liquid-vapor interface reaches the droplet boundary (liquid-liquid interface), bubble growth is similar to the well-studied bubble growth in a superheated liquid. As the thermal boundary layer reaches the liquid-liquid interface, the cooling of the bulk liquid also influences bubble growth rate. If the thermal conductivity of the bulk liquid is greater than the evaporating liquid, an increase in bubble growth rate is observed and the growth rate slows down if the thermal conductivity of the bulk liquid is lower. Similarly, it was seen that the bubble growth rate increases as the thermal mass of the bulk liquid increases. For each of the results presented, the bubble growth rate was seen to be similar in the initial stages of bubble growth and diverged only after the bubble diameter is over half the final diameter. More recently, Roesle and Kulacki [20] also developed a one-dimensional model to simulate boiling of small drops as well as the oscillations of the resulting bubble. They employed the momentum and energy conservation equations to simulate the growth and assume an initial uniform superheat throughout the droplet. Similar to Avedisian and Suresh [19], they find that the initial bubble growth is similar to bubble growth in an infinite medium and later stages of bubble growth are highly dependent on the surrounding liquid properties. They further found these effects to be more pronounced in larger droplets. The magnitude of the oscillations occurring after complete evaporation are also seen to increase with increasing thermal conductivity, density, and specific heat of the bulk liquid.

This paper presents a simplified method of determining the heat transfer and bubble growth within a liquid droplet surrounded by a superheated liquid. Contrary to previous models, the pressure driven phase of bubble growth is assumed to be negligible. This enables bubble growth to be modeled without the use of the momentum conservation equation which significantly simplifies the solving process without sacrificing accuracy. Furthermore, the initial temperature profile is not assumed to be at a uniform superheat as previously done. In order to better accommodate varying experimental conditions, the initial temperature profile is instead found using the heat diffusion equation. Using this methodology, concentric bubble growth is modeled and compared with varying experimental conditions. This model is limited to the growth of a bubble fully encompassed by the evaporating liquid. In certain situations, however, nucleation may occur at the liquid-liquid interface and the bubble remains there during evaporation. Alternatively, the film around the bubble may rupture once it reaches a critical thickness, resulting again in a bubble only