Applied Thermal Engineering 113 (2017) 639–652

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Surface-wettability-induced sliding bubble dynamics and its effects on convective heat transfer

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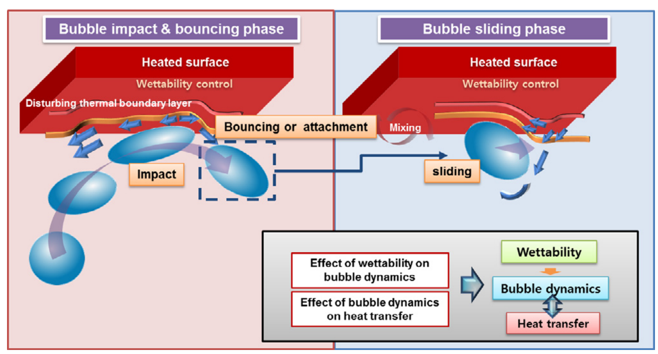
HIGHLIGHTS

- The effects of wettability on heat transfer in sliding bubble dynamics were explored.
- After a bubble collision, the bubble adheres to a heated hydrophobic surface.
- The bubble completely adheres to the surface as the adhesion force is increased.
- The heat transfer in the surface-contact regime is greater than that in other regimes.
- The surface more strongly affects the heat transfer in the surface contact region.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 16 June 2016
Revised 16 October 2016
Accepted 13 November 2016
Available online 14 November 2016

Keywords:
Sliding bubble
Surface wettability
Convective heat transfer
Volume of fluid
Nusselt number
Boundary layer

ABSTRACT

To explore the effects of wettability on heat transfer in sliding bubble dynamics, we investigated how the dynamics of sliding bubbles and heat transfer over a heated surface depend on the degree of wettability. We used volume-of-fluid scheme to track the interface of the dispersed phase via the local volume fraction. The results of the numerical model used in this study were consistent with those of experimental studies. After bubble collision, the bubble was found to adhere to a heated hydrophobic surface, as the bubble impinged upon the surface. The heat-transfer coefficient increased significantly in the region of the hydrophobic surface where the adhered bubble passed. The bubble completely adhered to the surface, as the adhesion force continuously increased. When the contact angle increased in the surface-contact regime (above 110°), the bubble spread out over the surface. The average Nusselt number in the surface-contact regime was found to be greater than that in other regimes (below 110°); thus, the surface more strongly affected heat transfer.

1. Introduction

Gas–liquid two-phase flow occurs in a wide range of modern industrial applications, such as power generation systems, electronic devices, and heat exchangers. In a two-phase-flow boiling system, the growth and dynamics of vapor bubbles have a dominant effect on convective heat transfer [1,2]. Thus, studying bubble dynamics is vital to understanding the mechanisms of flow boiling heat transfer. However, many prior investigations have focused mainly on bubble growth and detachment at nucleation sites [3–5]. Flow boiling heat transfer is strongly influenced by the motion of vapor bubbles after departure from nucleation sites [6–8]. After departure, bubbles show behaviors such as impingement, bouncing and sliding. Some researchers [11–16,26] have studied effect of these bubble behaviors on heat transfer. However,

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http://dx.doi.org/10.1016/j.applthermaleng.2016.11.097
1359-4311/

studies of bubble dynamics after departure are relatively rare; hence, their underlying mechanisms are not yet fully understood.

Several researchers have reported studies related to impingement and bouncing of a single bubble on a surface. Tsao and Koch [9] observed the interaction of high-Reynolds-number and moderate-Weber-number bubbles hitting solid walls. Albadawi et al. [10] investigated the collision with and bouncing off of a solid horizontal surface for a single isolated bubble, using numerical simulations based on the volume of fluid method (VOF). Bubble dynamics such as a bubble impacting and bouncing are associated with heat transfer. Donoghue et al. [11] experimentally investigated the coupled convective heat transfer and bubble motion that results from a single air bubble rising through water, and impacting and bouncing off of a heated horizontal surface. They reported that once the bubble hit the surface, there was a substantial variation in convective heat transfer.

Bubbles tend to slide along a heated surface after impingement, which is referred to as the standard "sliding bubble" phenomenon. Such sliding bubbles play an important role in the enhancement of heat transfer, an effect that is usually attributed to the evaporation of a thin microlayer underneath the bubble, and the mixing that occurs in the wake of the bubble and concomitant disruption of the thermal boundary layer [12,13]. Sateesh et al. [14] studied bubbles sliding along a vertical wall and a curved surface of a horizontal tube. They suggested that the mechanism of latent heat transfer or microlayer evaporation and the mechanism of transient conduction due to cyclic disruption and reformation of the thermal boundary layer take place simultaneously. In particular, Donnelly et al. [15] concluded that the mixing and disturbance of the thermal boundary layer caused by sliding bubbles could be important mechanisms for enhancing heat transfer. In addition, Houston and Cornwell [16] confirmed that heat transfer by evaporation of the microlayer under certain conditions is insignificant compared with other effects. Thus, other contributions to enhanced heat transfer, except for the effect of evaporation in microlayers, are considered to be important in the dynamics of sliding bubbles.

The flow characteristics of two-phase flow are affected by the wettability of a surface, which strongly influences the flow-regime transition in a system dominated by surface tension [17]. Krasowska and Malysa [18] studied bubble kinetics under different surface roughness conditions. They found that the attached time of a rising bubble varied depending on the degree of surface roughness. A number of researchers [19–21] discussed attractive forces resulting from hydrophobic surfaces. They reported that air bubbles adhere to hydrophobic surfaces due to attractive forces. Iguchi and Terauchi [22] evaluated how surface wettability influences the flow-regime transition in vertical air-water two-phase flows and proposed a bubbly-to-slug flow-transition criterion for hydrophobic pipes with a contact angle exceeding 100°. Fukushi and Iguchi [23] also suggested that bubble behavior is influenced by surface wettability. They found that bullet-like bubbles occur in a wetted pipe, whereas bubbles in a poorly wetted pipe rise along the pipe wall. Takamasa et al. [24] evaluated how surface wettability affects the characteristics of upward gas–liquid two-phase flow in a vertical pipe. In other work, Okawa et al. [25] studied how surface properties affect bubble dynamics in subcooled flow boiling and reported that bubbles are restricted to the wall to some extent when the contact angle with the heated surface exceeds a certain value.

To understand the details of the bubble–wall interaction, Akhtar et al. [26] simulated a growing vapor bubble approaching an inclined superheated wall. They found that the total heat flux from the wall becomes enhanced six- to seven-fold with respect to the precursor value during the initial interaction of a single FC-87 vapor bubble with the wall. In the sliding-bubble phenomenon, the bubble-surface interaction is an important issue [27] because bubbles slide along heated surfaces. Thus, how the wettability affects the flow characteristics of two-phase flow can be one of the important factors in flow-boiling heat-transfer systems. Nonetheless, data are limited on the effects of surface wettability on gas–liquid two-phase-flow characteristics in boiling heat-transfer systems.

As described above, surface wettability affects bubble movements. In addition, this effect can influence heat transfer. Thus, the objective of the present study is to explore how bubble dynamics affect convective heat transfer and to establish how surface wettability affects bubble dynamics (see Fig. 1). We investigated bubble characteristics and the heat-transfer rate near a heated surface with constant heat flux at a specific wall-inclination angle and Eotvos number (Eo) which represents a dimensionless number measuring the importance of surface tension forces compared to body forces. To study how surface wettability depends on contact angle, we used contact angles of 10–170° with respect to the heated surface. Thus, we analyzed bubble characteristics as a function of surface wettability and compared the heat-transfer rates of the various cases. Simulation results, including bubble dynamics and heat-transfer coefficients, were used to study how convective heat transfer by bubble dynamics is affected by surface wettability.

2. Computational methods

2.1. Governing equations

The governing equations for 3D incompressible flow include the continuity, momentum, and energy equations:

$$\nabla \cdot \boldsymbol{v} = 0, \tag{1}$$

$$\frac{\partial(\rho \boldsymbol{v})}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v}) = -\nabla p + \nabla \cdot \boldsymbol{R} + \rho \boldsymbol{f_b}, \tag{2}$$

$$\rho C_p\left(\frac{\partial \boldsymbol{T}}{\partial t} + v \cdot \nabla \boldsymbol{T}\right) = \Phi + \nabla \cdot (k \nabla \boldsymbol{T}\Big), \tag{3}$$

where $\boldsymbol{v}$ represents the velocity field shared by the two fluids throughout the flow domain, $\boldsymbol{R}$ is the deviatoric viscous stress tensor $\boldsymbol{R} = 2\mu\mathbf{S} - 2\mu(\nabla \cdot \boldsymbol{v})\mathbf{I}/3$, with a mean rate-of-strain tensor $\mathbf{S} = 0.5[\nabla\boldsymbol{v} + (\nabla\boldsymbol{v})^T]$ and $\mathbf{I} = \delta_{ij}$, ρ is density, p is pressure, $\boldsymbol{f_b}$ represents the body forces per unit mass, C_p is the specific heat capacity, $\mathbf{T}$ is a temperature field, Φ is the source term, k is thermal conductivity, and μ is dynamic viscosity.

2.2. Multiphase flow modeling

In this study, we consider a "two-phase-mixture" approach that uses a local vapor volume fraction and a transport equation with source terms for the mass transfer rate between the two phases:

$$\frac{\partial \gamma}{\partial t} + \nabla \cdot (\gamma \boldsymbol{v}) = 0. \tag{4}$$

Density and dynamic viscosities of the mixture are expressed by the vapor volume fraction γ:

$$\rho = \gamma\rho_v + (1-\gamma)\rho_l, \tag{5}$$

$$\mu = \gamma\mu_v + (1-\gamma)\mu_l, \tag{6}$$

where the subscripts v and l indicate "vapor" and "liquid," respectively.

The VOF method was first used by Hirt et al. [28] to track the interface of a fluid dispersed in a continuous fluid. In other words, this scheme tracks the interface of the dispersed phase by using the volume fraction γ within each individual cell. Cells without the interface have a value of zero or unity for the volume fraction γ. If $\gamma = 0$, the cell does not contain a continuous fluid and if $\gamma = 1$, the cell does contain a continuous fluid. Cells containing the