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Effects of wall slip and temperature jump on heat and mass transfer characteristics of an evaporating thin film ☆

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ABSTRACT

A new mathematical model is developed to predict heat and mass transport characteristics of the evaporating thin film. The model considers effects of velocity slip and temperature jump at the solid–liquid interface, disjoining pressure, and surface tension. Three-dimensional nonequilibrium molecular dynamics simulations for coupling between the momentum and heat transfer at the nanoscale solid–liquid interface are performed to obtain the slip length and interfacial thermal resistance length. It is found that both slip length and interfacial thermal resistance length decrease significantly with the decreasing interface wettability of the liquid to the wall. Velocity slip and temperature jump at the solid–liquid interface intend to reduce the superheat degree of the evaporating thin film, and thus result in a sharp decrease of the heat and mass transport characteristics of the evaporating thin film. It is also noted that velocity slip and temperature jump at the solid–liquid interface show a more pronounced effect as the superheat degree increases.

1. Introduction

High performance heat transfer devices or processes, such as heat pipes, vapor chambers, capillary pumped loops, spray cooling or nucleate boiling, achieve very high heat fluxes due to evaporation at thin liquid films [1,2]. The evaporating meniscus formed on a solid surface, as shown in Fig. 1, often divided into three distinct regions: equilibrium thin film, evaporating thin film, and intrinsic meniscus. The intrinsic meniscus is dominated by capillary forces, while the equilibrium thin film is governed by the disjoining pressure due to intermolecular interactions between the wall and the fluid. The evaporating thin film exists between the intrinsic meniscus and the equilibrium thin film, and is controlled by both capillary forces and disjoining pressure.

Shusser et al. [3] found that the instability of the evaporating thin film is caused by the increasing evaporation with the film thinning due to higher heat flux. Ji et al. [4] employed molecular dynamics method to get a microscopic insight into the complex liquid–vapor–solid system. Potash et al. [5] assumed that the pressure gradient for liquid flow was due to both capillarity and disjoining pressure. Holm et al. [6] used a wedge flow model to investigate the liquid flow in the evaporating thin film. Stephan et al. [7] found that the assumption of interface temperature equal to the saturation temperature of the vapor can lead to a large overprediction of the radial heat transfer coefficient. Krustalev et al. [8] discussed the influence of fluid flow on heat and mass transport characteristics of the evaporating thin film. Gorla [9] developed a new mathematical model subjected to van der Waals attractive forces and the electric field. Park et al. [10] concluded that the decreased film thickness causes the capillary and disjoining pressures to increase in slip condition. Wee et al. [11] incorporated the effects of the working fluid polarity, the slip boundary condition, and thermocapillary stresses on heat and mass transfer characteristics of the evaporating thin film. Panchamgam et al. [12] applied image analyzing interferometry to analyze the thickness profile for a moving evaporating thin liquid film. Wee et al. [13] examined the effect of binary mixture (pentane/decane) on the flow and heat of an evaporating meniscus. Ma et al. [14] utilized the order analysis to simplify the N–S momentum equation. Wang et al. [15] obtained an analytical solution for the total heat transfer in evaporating thin film. Bertossi et al. [16] performed a parametric study on the thin liquid film in the evaporator of the heat pipes. Recently, Maroo et al. [17] found that a force function of the form $F_n = \mathrm{A}n^{-3} - \mathrm{C}n^{-2}$ can be applied at the boundaries of a liquid film to create curvature and form a meniscus.

At the micro-/nano-scale, the shear flow of liquid past a solid surface is known to generate a velocity slip as shown in Fig. 1. By the Navier boundary condition, slip velocity can be expressed as

$$\Delta u_i = l_s \frac{\partial u}{\partial y}\bigg|_{y=0} \tag{1}$$

where l_s is the slip length defined as the fictitious distance inside the solid at which the no-slip flow boundary condition is satisfied as shown in Fig. 1.

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