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Comparison of different analytical models for heat and mass transfer characteristics of an evaporating meniscus in a micro-channel☆

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A R T I C L E I N F O

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A B S T R A C T

Based on the augmented Young–Laplace equation and lubrication theory, a detailed analytical model predicting the heat and mass transport characteristics of the evaporating meniscus in a micro-channel is developed. The present model solves the third-order differential equation of the film thickness and the first-order differential equation of the liquid average velocity simultaneously. The different models for thermal performance of the evaporating meniscus are also compared to each other. It is found that both the film thickness and cumulative heat flux by the present model are in good agreement with the results by the previous models. The total heat flux of evaporating meniscus based on interface temperature calculated by Clausius–Clapeyron equation is far higher than that obtained by Wayner's interface mass flux model.

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1. Introduction

Phase change heat transfer devices or processes, such as heat pipes, vapor chambers, capillary pumped loops or nucleate boiling, can achieve very high heat fluxes due to thin film evaporation which takes place on the liquid–vapor interface of heated meniscus [1,2]. An evaporating extended meniscus developed on the wall within a micro-channel is shown in Fig. 1. It consists of three distinct regions: the equilibrium thin film, the evaporating thin film and intrinsic meniscus. In the equilibrium thin film, the interfacial thermal resistance is so large that the liquid–vapor interface temperature is equal to the wall temperature, and thus the evaporation phenomenon does not occur in this region. The intrinsic meniscus is dominated by capillary forces. The evaporating thin film, which exists between intrinsic meniscus and the equilibrium thin film, is controlled by capillary forces and disjoining pressure due to intermolecular interactions between the wall and the liquid.

In order to establish the thin film thickness, the concept of a disjoining pressure, caused by intermolecular solid–liquid forces, was introduced by Derjaguin [3]. Wayner et al. [4] suggested the evaporative mass flux as a function of temperature and pressure at the interface based on Kelvin–Clapeyron equations. Mirzamoghadam and Catton [5] used an appropriate liquid velocity and temperature distribution in an integral approach similar to boundary layer analysis to obtain the evaporating meniscus profile. Stephan and Busse [6] concluded that the assumption of liquid–vapor interface temperature equal to the saturation temperature of vapor can lead to a large overprediction of the radial heat transfer coefficient. Gorla [7] found that the electric field can significantly enhance heat transfer of the evaporating meniscus. Wee et al. [8] concluded that the slip effect of elongating the evaporating thin film region can counteract the thermocapillary action of reducing the region. Wang et al. [9] found that the micro-region is found to account for more than 50% of the total heat transfer of the evaporating meniscus. Ma et al. [10] made use of order analysis to simplify the N–S momentum equation of evaporating thin film. Xia et al. [11] investigated capillary-assisted evaporation of an inclined micro-groove analytically. Bertossi et al. [12] performed a parametric study on the evaporating meniscus in the evaporator of heat pipes. Zhao et al. [13] showed that the nanofluid can greatly increase the thin film heat transfer. Du and Zhao [14] developed new boundary conditions for the evaporating meniscus. Benselama et al. [15] used a linear stability analysis approach to study the evaporating thin film. Pati et al. [16] revealed that the electrostatic component of disjoining pressure can elongate the evaporating meniscus. Bai et al. [17] developed a hybrid axial groove based on thin film evaporation theory and the fundamental operating principles of heat pipes. Guo et al. [18] investigated effects of vertical mechanical vibration on evaporation heat transfer characteristics in rectangular microgrooves.

In this paper, an analytical model for heat and mass transfer characteristics of an evaporating meniscus in a micro-channel is presented. The present investigation complements previous studies in two ways. First, the present model associates the liquid average velocity directly with the liquid pressure gradient through the mass flow rate, and the third-order differential equation of the film thickness and first-order differential equation of the liquid average velocity are presented. Only first-order derivative of the liquid pressure with respect to x is need,

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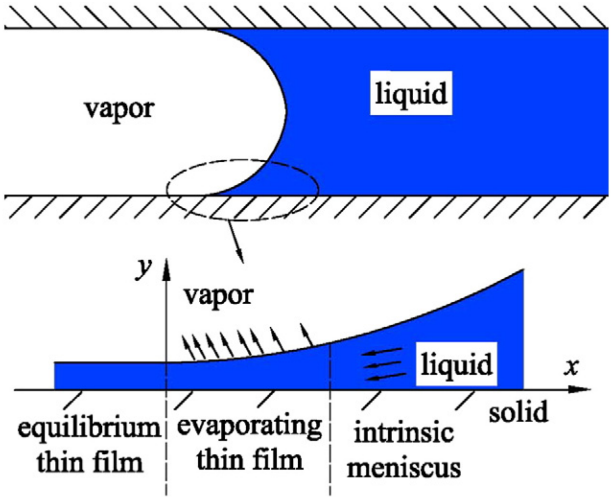

Fig. 1. The evaporating meniscus in a micro-channel.

rather than the second-order derivative of the liquid pressure in previous model. Second, this paper compares the thermal performance of the evaporating meniscus obtained by Model 2 (interface temperature calculated by Clausius–Clapyron equation [5,6,10,12,13,18]), and Model 3 (Wayner's interface mass flux model [4,7,8,11,14,15,17]) for the first time. It is found that the total heat flux of the evaporating meniscus obtained by Model 3 is far lower than that obtained by Model 2.

2. Theoretical analysis

2.1. Mathematical modeling

In the thin film region, the pressure jump across the liquid–vapor interface is calculated by the augmented Young–Laplace equation

$$P_v = P_l + P_d + P_c \tag{1}$$

where P_v is the vapor pressure. P_l is the liquid pressure. P_d is the disjoining pressure. P_c is the capillary pressure.

The disjoining pressure is due to the long-range van der Waals forces between the liquid and the solid over a narrow range of film thicknesses, and is determined by

$$P_d = \frac{A}{\delta^3} \tag{2}$$

where A is the dispersion constant, and δ is the film thickness.

The capillary pressure is expressed as

$$P_c = \sigma K, \quad K = \frac{d^2\delta}{dx^2}\left[1+\left(\frac{d\delta}{dx}\right)^2\right]^{-3/2} \tag{3}$$

where σ is surface tension, and K is meniscus curvature.

Assuming uniform vapor pressure distribution along the evaporating meniscus, Eq. (1) is differentiated with respect to x as

$$\frac{d^3\delta}{dx^3} - 3\frac{d\delta}{dx}\left(\frac{d^2\delta}{dx^2}\right)^2\left[1+\left(\frac{d\delta}{dx}\right)^2\right]^{-1} + \frac{1}{\sigma}\left(\frac{dP_l}{dx} - \frac{3A}{\delta^4}\frac{d\delta}{dx}\right)\left[1+\left(\frac{d\delta}{dx}\right)^2\right]^{3/2} = 0. \tag{4}$$

Lubrication theory is often used for the liquid flow in the thin film region. Applying a no-slip boundary condition at solid–liquid interface and a stress free boundary condition at liquid–vapor interface, the mass flow rate along x direction is related to the liquid pressure gradient as:

$$\Gamma = -\frac{\rho_l}{3\mu_l}\frac{dp_l}{dx}\delta^3 \tag{5}$$

where μ_l is the liquid dynamic viscosity, and ρ_l is the liquid density.

The evaporation heat flux at the liquid–vapor interface is equal to the one-dimensional conduction heat flux through the thin film, thus giving

$$-\frac{\partial \Gamma}{\partial x}h_{fg} = \frac{d}{dx}\left(\frac{1}{3\nu_l}\frac{dp_l}{dx}\delta^3\right) = \frac{(T_w - T_{iv})}{\delta/k_l} \tag{6}$$

where h_{fg} is the latent heat of evaporation, k_l is the liquid thermal conductivity, T_w is the solid wall temperature, and T_{iv} is the liquid–vapor interface temperature.

Combining Eqs. (4) and (6), the fourth-order ordinary differential equation (ODE) for thin film thickness δ with respect to x is obtained, and is widely used in most of previous investigations.

Next, this paper will present a third-order ODE for the thin film thickness. The mass flow rate along the x direction is also related to the liquid velocity as

$$\Gamma = \rho_l\int_0^\delta u\,dy = \rho_l\delta\bar{u} \tag{7}$$

where u is the liquid velocity along the x direction, and $\bar{u}$ is liquid average velocity.

Substituting Eqs. (7) and (5) into Eq. (4), the third-order ODE for δ is obtained as

$$\frac{d^3\delta}{dx^3} - 3\frac{d\delta}{dx}\left(\frac{d^2\delta}{dx^2}\right)^2\left[1+\left(\frac{d\delta}{dx}\right)^2\right]^{-1} - \frac{1}{\sigma}\left(\frac{3\mu_l\bar{u}}{\delta^2} + \frac{3A}{\delta^4}\frac{d\delta}{dx}\right)\left[1+\left(\frac{d\delta}{dx}\right)^2\right]^{3/2} = 0. \tag{8}$$

The evaporation heat flux at the liquid–vapor interface is equal to the one-dimensional conduction heat flux through the thin film as

$$q' = -\frac{\partial(\rho_l\delta\bar{u})}{\partial x}h_{fg} = \frac{(T_w - T_{iv})}{\delta/k_l}. \tag{9}$$

Expanding Eq. (9) gives:

$$\frac{d\bar{u}}{dx} = -\frac{k_l(T_w - T_{iv})}{\rho_l h_{fg}\delta} - \frac{\bar{u}}{\delta}\frac{d\delta}{dx}. \tag{10}$$

By solving Eq. (8) (a third-order ODE for film thickness) and Eq. (10) (a first-order ODE for liquid average velocity) simultaneously, the thin film thickness and average liquid velocity can be obtained. This model is named as Model 1 (M1) in this paper.

The liquid–vapor interface temperature T_{iv} in Eqs. (6) and (10) can be determined through two classic methods. The first method is integrating the Clausius–Clapyron equation. Expanding the Clausius–Clapeyron equation [5]

$$\left(\frac{dP}{dT}\right)_{sat} = \frac{h_{fg}}{T_v\left({}^{1}/_{\rho_v} - {}^{1}/_{\rho_l}\right)} \tag{11}$$

gives:

$$\frac{T_v dP_v}{\rho_v} = \frac{T_v dP_l}{\rho_l} + h_{fg}dT. \tag{12}$$

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