International Journal of Heat and Mass Transfer 73 (2014) 849–858

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Thermocapillary flow in evaporating thin liquid films with long-wave evolution model

Elaine Lim, Yew Mun Hung *

School of Engineering, Monash University, 46150 Bandar Sunway, Malaysia

A R T I C L E I N F O

Article history:
Received 21 December 2013
Received in revised form 25 February 2014
Accepted 26 February 2014
Available online 27 March 2014

Keywords:
Evaporating thin film
Marangoni effect
Surface tension
Thermocapillary flow

A B S T R A C T

The thermocapillary convection is induced along a liquid–vapor interface due to surface tension gradient which is temperature dependent. The impact of thermocapillary effect on the thermal behavior of an evaporating thin liquid film is investigated in this work. By employing the long-wave evolution model, a mathematical model based on first principles for fluid flow and heat transfer is derived for the interface shapes that govern the thickness of the evaporating thin film. The two-dimensional information of the liquid temperature which is a prerequisite for the incorporation of the thermocapillary effect can be obtained. The analysis provides a well-defined exposition of the significance of such effect in thin-film evaporation, scrutinizing the changes entailed in the heat transfer characteristics. The evaporation rate is overrated when the thermocapillary effect is neglected and the overestimate increases with increasing excess temperature. This study reveals the conditions under which the thermocapillary effect is significant and should not be neglected in the heat transfer analysis of an evaporating thin film.

1. Introduction

The evaporating and shear-driven thin film near the three phase contact line plays an important role in the micro-scale cooling devices such as micro heat pipes [1–3]. Owing to the demanding needs for electronics cooling and advances in miniaturization of electronic components, micro heat pipe has manifested itself as an effective cooling device for electronic components. As a high heat flux is involved in the evaporating section of two-phase devices with capillary structures, the thin film evaporation heat transfer plays a vital role in the heat transfer characteristics. A better understanding of the transport phenomena of the evaporating and shear-driven thin film near the three phase contact line is crucial in predicting the performance characteristics of various two-phase devices with capillary structures.

When a liquid film wets a solid wall and evaporates, typically the extended meniscus can be divided into three regions, namely the equilibrium non-evaporating film region, the evaporating film region, and the intrinsic meniscus region [4,5]. Fig. 1 illustrates the three regions of an extended meniscus. An adsorbed or non-evaporating film region consists of ultra-thin liquid film which is adsorbed on the wall. In the evaporating film region, the flow is driven by capillary force and disjoining pressure gradient. The disjoining pressure, which represents the change in the body force of the liquid due to the long-range van der Waals forces between the solid and the liquid, plays a key role in affecting the interface temperature and heat transfer rate through the thin film [6]. In the intrinsic meniscus region, the capillary force dominates. It has been pointed out in numerous previous studies that high heat transfer rate takes place in the evaporating film region due to the low thermal resistance [7–10].

The Marangoni effect is identified by the presence of surface tension gradient which causes the liquid to flow away from regions of low surface tension. The surface tension gradient can be caused by a concentration gradient or a temperature gradient. Due to the large increase in surface area relative to volume, surface tension has a dominant effect on the fluid behavior in a capillary structure. For small-Reynolds-number flow in a capillary structure, the surface tension gradient becomes increasingly important and this gradient would affect its thermal performance which is very much dependent on the capillarity as a result of surface tension [11]. Evaporation of a thin film induces temperature gradient and hence surface tension gradient along the liquid-vapor interface, leading to Marangoni convection which is regarded as thermocapillary flow [12]. The highest local vapor diffusion gradient at the triple contact line results in the strongest evaporation which is coupled with the low thermal resistance to form Marangoni convection. The surface tension of most liquids decreases with increasing temperature and the thermocapillary stresses generate an

* Corresponding author. Tel.: +60 3 5514 6251; fax: +60 3 5514 6207.
E-mail address: hung.yew.mun@monash.edu (Y.M. Hung).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.02.065
0017-9310/

Nomenclature

A	non-dimensional Hamaker constant
A'	Hamaker constant (J)
C	capillary number
E	evaporation number
h_e	local heat transfer coefficient (W/m^2 K)
$\mathbf{I}$	identity tensor
J	mass flux (kg/s m^2)
k	thermal conductivity (W/m K)
K	parameter of degree of non-equilibrium at the evaporating interface
l_e	evaporating film length (m)
L	latent heat of vaporization (J/kg)
M_w	molecular weight (kg/mol)
M	Marangoni number
$\mathbf{n}$	unit normal vector
p	liquid pressure (Pa)
$p^{(v)}$	vapor pressure (Pa)
P	Prandtl number
q''_e	local evaporative heat flux (W/m^2)
$\bar{R}$	universal gas constant (J/mol K)
R	radius of curvature (m)
S	non-dimensional surface tension
$\mathbf{t}$	unit tangent vector
T	local surface temperature (K)
ΔT	excess temperature (K)
T_s	saturation temperature (K)
T_w	wall temperature (K)
$\mathbf{T}$	liquid stress tensor (Pa)
$\mathbf{T}^{(v)}$	vapor stress tensor (Pa)
v	liquid velocity (m/s)
x	horizontal coordinate (m)
y	vertical coordinate (m)

Greek symbols

α	accommodation coefficient
δ_0	adsorbed film thickness (m)
δ	liquid film thickness (m)
γ	surface tension gradient (N/m K)
κ	thermal diffusivity (m^2/s)
λ	wave number
μ	dynamic viscosity (N s/m^2)
ν	kinematic viscosity (m^2/s)
ρ	liquid density (kg/m^3)
$\rho^{(v)}$	vapor density (kg/m^3)
σ	surface tension (N/m)
σ_0	surface tension at saturation reference temperature (N/m)
τ	rate of deformation tensor in liquid (s^{-1})
Δ	mean curvature of interface (m^{-1})
Π	disjoining pressure (Pa)

interfacial flow from high to low temperature regions, driving a nearly parallel flow toward the low-temperature region in the streamwise direction. Based on the fact that the streamwise temperature in various microdevices can be customarily controlled, the resulting thermocapillary stresses impose a significant degree of control over the flows in such devices [13]. Most studies dealing with the thermocapillary effect addressed the transient problem associated with the instability phenomena, just to name a few of them here [14–19]. Burelbach et al. [14] derived the long-wave evolution equations to analyze the interface shapes associated with the two-dimensional nonlinear instabilities of the thin film induced by vapor recoil, thermocapillary, and rupture effects. The lubrication theory was deployed for the non-isothermal, evaporating layer with the dependent variables varying slowly along the plate while the temperature profile and the film thickness were considered changing rapidly inside the evaporating thin film. They used the long-wave theory in shear flows which are marginally unstable to disturbances with infinite scale in the streamwise direction and the long-wave disturbances periodic in such direction were defined using a small parameter denoted as the wave number. On the other hand, for steady-state investigations, despite the significance of the evaporation induces temperature gradient and surface tension gradient along the interface, most theoretical studies of transport phenomena of evaporating meniscus in microscale devices excluded the thermocapillary stresses [10,20–28]. The surface tension is a function of the liquid temperature but the above-mentioned studies [10,22–27] neglected the differences between the liquid and the vapor temperatures at the interface, following the widely used evaporative mass flux model which employs the extended Clapeyron equation in approximating the vapor temperature [5]. It has been pointed out that the neglect of the differences between the liquid and the vapor temperatures at the interface leads to an overestimate on the heat transfer coefficient [8]. Furthermore, the information of the liquid temperature and

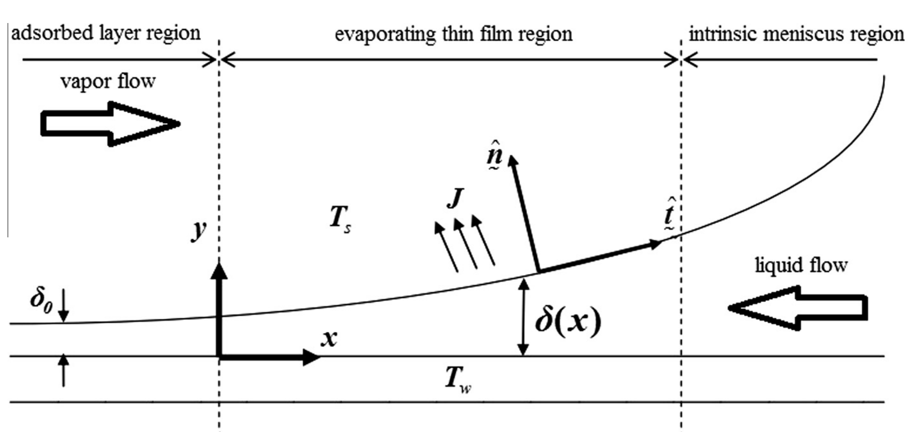

Fig. 1. A schematic diagram of an evaporating thin film depicting the adsorbed layer region, the evaporating thin film region and the intrinsic meniscus region.