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A hydrodynamic analysis of thermocapillary convection in evaporating thin liquid films

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ABSTRACT

Evaporation in a thin film induces pronounced temperature gradient and surface tension gradient along the liquid-vapor interface and in turn engenders thermocapillary flow. This study aims to investigate the fluid flow characteristics attributed to the thermocapillarity in an evaporating thin liquid film of polar and nonpolar liquids. A numerical steady-flow model is derived based on the fundamental principles of fluid flow and heat transfer by applying the long-wave evolution technique. To scrutinize the underlying physical transport phenomena associated with the significance of thermocapillary effect in an evaporating thin liquid film, we investigate the hydrodynamic characteristics of thermocapillary convection which is typically characterized by the recirculation flow patterns. The two-dimensional recirculation flow patterns in different excess-temperature regimes are analyzed and a critical turning point at where the flow is reversed due to the thermocapillary action can be identified. Compared to other working fluids, water depicts a unique thermocapillary flow characteristic where its flow lines manifests in the form of swirls along the liquid-vapor interface. The normal and the shear stress distributions further provide a clearer picture on the strength of thermocapillarity to identify the manifestation of thermocapillary flow. The analysis of flow patterns and hydrodynamic behaviors of evaporating thin liquid films provide essential insights in discerning the occurrence of thermocapillary flow as well as the significance of thermocapillarity in polar and nonpolar liquids.

1. Introduction

The intricate solid-liquid and liquid-vapor interfacial interactions of an evaporating thin liquid film intrinsically influence the heat and fluid flow characteristics. Fig. 1 illustrates a schematic diagram of an evaporating thin liquid film. The liquid film layer can be divided into three regions, namely adsorbed layer region, evaporating thin film region and intrinsic meniscus region [1–3]. The adsorbed layer region is also known as non-evaporating region. The adsorbed film which is suppressed by disjoining pressure is extremely thin and evaporation does not take place in this region [2,3]. As disjoining pressure diminishes in the evaporating thin film region, the low thermal resistance in this region leads to high evaporation rates [4,5]. The liquid is circulated from the intrinsic meniscus region, such that it is driven from a low-temperature region to a high-temperature region to maintain the evaporation rates [6,7]. The temperature gradient leads to the surface tension gradient during the evaporation process [8,9]. The effect of surface tension gradient induces thermocapillary flow which drives the liquid from a low-surface-tension region to a high-surface-tension region [10,11]. The high-surface-tension strength of the intrinsic meniscus region imposes an opposing force which prevents the liquid from flowing to the evaporating thin film region, as depicted in Fig. 1. The effect of surface tension gradient essentially affects the capillarity of a microscale phase-change heat transfer device when the ratio of surface area relative to volume is large [12].

Thermocapillary effect has been observed in an evaporating thin film of polar and nonpolar liquids [13]. The disjoining pressure is strongly associated with the polarity [14–16] and the thermo-physical properties [7] of a working fluid which significantly influence the thermal and fluid characteristics. From the aspect of thermal behavior, our recent study [13] demonstrated that different liquid temperature gradient magnitudes attributed to the variations of thermo-physical properties lead to different degree of thermocapillary effect on the thermal characteristics. The liquid temperature gradient is intimately related to the excess temperature, which in turn affects the thermocapillary strength of an evaporating thin film. The thermocapillary effect is observed to be more

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Nomenclature

A	non-dimensional Hamaker constant
A'	Hamaker constant (J)
C	capillary number
E	evaporation number
$\mathbf{I}$	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_c	critical turning-point length (m)
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})
Π	disjoining pressure (Pa)

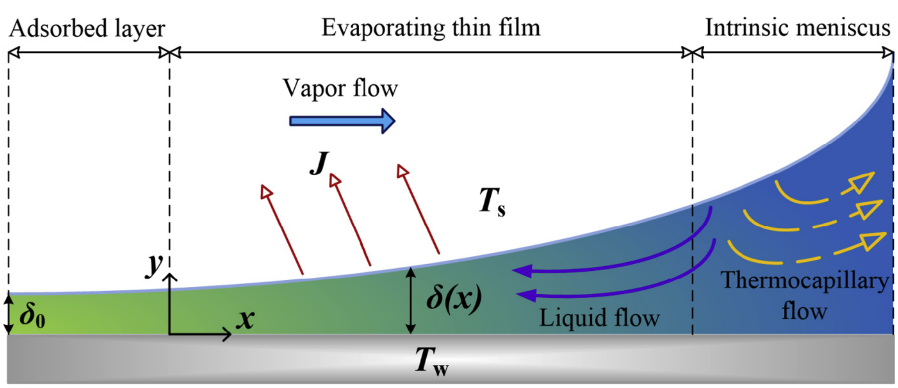

Fig. 1. A schematic illustration of an evaporating thin film depicting the transport phenomena in the adsorbed layer region, the evaporating thin film region and the intrinsic meniscus region.

significant at higher excess temperature [3,13]. When a low excess temperature of less than 10 K is applied, thermocapillary effect is deemed to be insignificant in the evaporating thin liquid film [4,17]. The Marangoni number, defined as the ratio of surface tension force to viscous force, is used as a manifestation of thermocapillary flow [18]. It can be shown that for a thermocapillary evaporation, the Marangoni number is proportional to the excess temperature [3,13]. When the Marangoni number is less than its critical value, the thermocapillary effect is considered to be absent. While thermocapillary convection prevails in most of the volatile liquids [19,20], its presence in water, a strong polar liquid, remains a subject of controversy [21–25]. A number of studies have shown that the thermocapillary convection is insubstantial in the water despite its Marangoni number is much greater than the critical value. The thermocapillary flow in water is assumed to be suppressed by the surface contaminants as the presence of impurities or surface active agents on the water surface counteracts the thermocapillary flow in water [21,26,27]. On the other hand, the prevalence of interfacial temperature gradient suggested the existence of thermocapillary convection in pure water [28–32]. Therefore, the claim that the thermocapillary effect is significant in water remains ambiguous.

To scrutinize the underlying physical transport phenomena associated with the significance of thermocapillary effect in an evaporating thin liquid film, we extend our study to numerically investigate the hydrodynamic characteristics of thermocapillary convection in this paper. Thermocapillary flow is typically characterized by the recirculation pattern [33–36]. The analysis of flow patterns and hydrodynamic behaviors of evaporating thin liquid films would be essential in discerning the occurrence of thermocapillary flow as well as the significance of thermocapillarity in polar and nonpolar liquids. From the streamline plots, the turning point which characterizes the occurrence of thermocapillary flow can be identified. By analyzing the normal and the shear stress distributions, a clearer picture on the strength of thermocapillarity can be obtained. The direction and velocity of the thermocapillary flow are dependent on the excess temperature and hence the recirculation flow patterns in different excess-temperature regimes are