International Journal of Thermal Sciences 134 (2018) 612–621

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Heat transfer characteristics of a binary thin liquid film in a microchannel with constant heat flux boundary condition

Leping Zhou[a,*], Shengni Zhou[a,b], Xiaoze Du[a], Yongping Yang[a]

[a] School of Energy, Power and Mechanical Engineering, Key Laboratory of Condition Monitoring and Control for Power Plant Equipment of Ministry of Education, North China Electric Power University, Beijing, 102206, China

[b] Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou, 510070, China

ARTICLE INFO

Keywords:
Thin film
Binary fluid
Temperature
Channel size
Non-condensable gas

ABSTRACT

Thin film evaporation of multi-component fluids in microchannels is important in many industrial applications, which requires comprehensive modeling of the transport mechanisms in the liquid, gas and solid phases. This paper presents a numerical study on the heat transfer characteristics of a binary thin liquid film in a microchannel with constant heat flux boundary condition, using the enhanced Young-Laplace equation that considers the effect of disjoining pressure for binary fluids. Effects of temperature, microchannel size, and non-condensable gas on the binary thin film heat transfer was analyzed. The results show that the thin film contribution to the total heat transfer rate reduces when the initial temperature increases, but the difference between them decreases as the microchannel size reduces. Size effect can be prominent when the characteristic microchannel size is smaller than 10 μm. When the microchannel size decreases, the cumulative heat transfer rate across the interface of the solution decreases, while the thin film contribution to the total heat transfer rate increases obviously. The non-condensable gas deteriorates the cumulative heat transfer rate, but the deterioration reduces under the high temperature condition as compared to that under the low temperature condition. Comparison of the results shows that the temperature and microchannel size have the greatest effect on the heat transfer followed by the non-condensable gas. This can be efficiently utilized for heat transfer enhancement and thermal design in applications involving phase-change heat transfer of multi-component fluids in microchannels.

1. Introduction

Thin film evaporation occurs in a region which is a few microns near the triple line during bubble growth in boiling [1], droplet evaporation [2], film dryout [3], and spray cooling [4] in a variety of phase-change systems including heat pipes, vapor chambers, and cold plates. This phenomenon was controlled by the liquid disjoining pressure gradient and the pressure and temperature differences at the liquid-vapor interface [5], and an intensive evaporation near the three phase junction has been believed to be the dominant heat transfer mode in such microscale systems [6]. The temperature gradient along the meniscus results in a surface tension gradient that gives rise to thermocapillary convection, which along with the thin film evaporation have been reported to the main contributor to the total heat transfer [7,8].

The pressure and temperature distribution, thin film profile, and heat and mass transfer near triple line have been studied extensively in the literature [9]. The effect of thermocapillary convection on flow pattern, hydrodynamic behavior, and evaporation rate of a thin film in polar or nonpolar liquid was investigated using a long-wave evolution model [10]. The thermocapillary effects on the stability of evaporating thin liquid film was studied accounting for surface forces using a perturbative local analysis approach [11]. Detailed modeling of thin film heat transfer requires consideration of the effects of interfacial evaporation and thermocapillary convection, together with the natural convection and vapor transport in the gas phase [12]. A complete expression using an augmented Young-Laplace model and the kinetic theory-based expression for interfacial mass transport was employed with appropriate boundary conditions for modeling of thin film evaporation [13,14]. Recently, Hanchak et al. [15] formulated a numerical model for predicting the transient thin film thickness and instantaneous heat transfer coefficient. Their work includes transient lubrication theory of liquid flow within the film, heat conduction across the film from the heated wall to the liquid-vapor interface, kinetic theory of evaporation from the interface to the vapor phase, and disjoining pressure based on a retarded van der Waals interaction.

In a microchannel, the extended meniscus has a capillary-dominated

* Corresponding author.
E-mail address: lpzhou@ncepu.edu.cn (L. Zhou).

https://doi.org/10.1016/j.ijthermalsci.2018.08.043
Received 1 February 2018; Received in revised form 26 August 2018; Accepted 27 August 2018
1290-0729/

Nomenclature

A	proportional constant thermal diffusivity ($m^2 \cdot s^{-1}$)
A	area (m^2) Hamaker constant (J)
B	proportional constant
C	molar concentration ($mol \cdot m^{-3}$) accomodation coefficient
D	diffusion coefficient ($m^2 \cdot s^{-1}$)
E	apparent energy ($J \cdot kg^{-1}$)
F	volumetric force (N)
G	gravity acceleration ($m \cdot s^{-2}$)
H	height (m)
h_{fg}	latent heat of evaporation ($J \cdot kg^{-1}$)
j_m	interfacial net mass flux ($kg \cdot m^{-2} \cdot s^{-1}$)
k	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
K	interfacial curvature (m^{-1})
L	characteristic length (m)
$P_v = P_l + P_c + P_d$	molecular weight ($kg \cdot mol^{-1}$)
Ma	Marangoni number
$\boldsymbol{N}$	unit normal vector
P	pressure ($N \cdot m^{-2}$)
P_c	capillary pressure ($N \cdot m^{-2}$)
P_d	disjoining pressure ($N \cdot m^{-2}$)
P_l	liquid pressure ($N \cdot m^{-2}$)
P_{sat}	saturation pressure ($N \cdot m^{-2}$)
P_v	vapor pressure ($N \cdot m^{-2}$)
P_{v_equ}	equilibrium pressure ($N \cdot m^{-2}$)
Q	heat flow rate ($W \cdot m^{-2}$)
Q	cumulative heat transfer ($W \cdot m^{-1}$)
R	contact radius (m)
R	droplet radius (m)
$P_d = -\frac{A}{6\pi\delta^3}$	universal gas constant ($J \cdot mol^{-1} \cdot K^{-1}$)
Ra	Rayleigh number
S_e	source term due to heat transfer ($J \cdot m^{-3} \cdot s^{-1}$)
S_m	source term due to mass transfer ($kg \cdot m^{-3} \cdot s^{-1}$)
$\boldsymbol{T}$	unit tangential vector
T	temperature (K)
V	velocity ($m \cdot s^{-1}$)
x	length along the film (m)
y	height along the film thickness (m)

Greek symbols

A	volume fraction
B	thermal expansion coefficient ($m \cdot K^{-1}$)
Δ	liquid film thickness (m)
δ_0	non-evaporating layer thickness (m)
μ	dynamic viscosity ($kg \cdot m^{-1} \cdot s^{-1}$)
ν	kinematic viscosity ($m^2 \cdot s^{-1}$)
θ	contact angle (°)
ρ	density ($kg \cdot m^{-3}$)
σ	surface tension coefficient ($N \cdot m^{-1}$)

subscripts

air	air
atm	atmosphere
cell	cell
diff	diffusion
f	cell interface
g	gas
i	interface
l	liquid
lv	interface
net	net value
ref	reference state
sat	saturated
total	total value
v	vapor
w	wall

thicker portion of the thin film in which the lubrication theory is not valid, therefore the apparent contact angle has a large effect on heat transfer because of its effect on capillary suction and the area of the meniscus [16]. Park et al. [17] considered the gradients of vapor pressure and capillary force, proposed a mathematical model for predicting the flow and heat transfer characteristics in the thin film region of a microchannel, and investigated the effects of channel height, heat flux and slip boundary condition at the solid-liquid interface. Du and Zhao [18] developed new boundary conditions that ensure the center of the intrinsic meniscus is on the axis of the microchannel. The interface between the thin-film region and the intrinsic region is better matched and the thin film region can be cumulatively smooth with the bulk liquid region. They subsequently proposed a full model for conjugate heat transfer in the evaporating thin film, the substrate, and the intrinsic liquid, to study the heat transfer characteristics in the contact line region in a microchannel [19]. Zhao et al. [20] investigated the effects of adsorbed film thickness, channel height, and temperature-dependent thermophysical properties of the fluid in the model at wall superheats up to 50 K. They also included the effect of thin porous coating formed by nanoparticle deposition on the surface wettability [21]. Their results show that the constant thermophysical property model greatly overestimates the liquid pressure difference and the total thin film heat transfer rate at higher superheats, and the coating can significantly reduce the thin film evaporation with increasing layer thickness and hence augmented thermal resistance. Biswal et al. [22,23] investigated the effect of disjoining pressure and interfacial slip on the thin film evaporation in a microchannel. Interfacial slip can elongate and thicken the thin film, resulting in lower interfacial heat and mass transfer rates in the thin film region, but the total evaporation turns out to be higher due to the longer film length. When the slope and curvature dependence of the disjoining pressure was taken into account, it allows an asymptotic merging of the evaporating interfacial profile to the adsorbed film and prevents the contact line movement without slip. A combined influence of disjoining pressure and interfacial slip is a nonlinear alteration in the thin film profiles [24]. Recently, Mandel et al. [25] developed a model to simulate the performance of a microgrooved heatsink undergoing organized, steady state, thin film evaporation subjected to a superheat at its base. The effects of base superheat, channel width, fin-channel width ratio, and channel aspect ratio on the base heat transfer coefficient were evaluated. An optimized geometry which is capable of dissipating 320 W/cm^2 with 10 K base superheat using octane was suggested.

These studies have mainly been for pure fluids with few reported studies of binary thin liquid film. Binary fluids were suggested to be used for counteracting the thermocapillary convection and delaying the onset of thin film instability through the solutocapillary convection [26]. Kern and Stephan [27,28] conducted a series of theoretical works on thin film heat transfer for binary fluids. Wee et al. [29] developed a comprehensive model to calculate the binary thin film profile and to study its effect on heat and mass transfer in evaporating meniscus. However, although there have been efforts to incorporate either some or all of the transport mechanisms in the liquid, gas and solid phases [30–33], the details of the transport process in a binary thin liquid film need to be thoroughly studied due to the complexity of binary fluid evaporation. Further investigation need to be conducted under conditions that are more comprehensive such as in a microchannel, and more