



# Heat transfer characteristics of evaporating thin liquid film in closed microcavity for self-rewetting binary fluid



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## ARTICLE INFO

### Article history:

Received 5 August 2016

Received in revised form 20 November 2016

Accepted 7 December 2016

### Keywords:

Evaporation

Thin film

Binary fluid

Self-rewetting

Size

## ABSTRACT

The heat transfer characteristics of aqueous *n*-butanol solution in the thin film region of closed microcavity, based on an enhanced Young-Laplace equation that includes the contribution of disjoining pressure for self-rewetting binary fluids, was numerically investigated. The effects of fluid properties, non-condensable gas, and system geometry on the thin film heat transfer were discussed. The results indicate that the heat transport capability of 5.0 wt% *n*-butanol solution is superior to water in the thin film region. The thin film contribution to the net heat transfer rate increases substantially if the wettability of the binary fluid increases. The mass flux and the heat transfer rate in the thin film region can be slightly deteriorated if there exists non-condensable gas near the interface, but the effect of the non-condensable on the thin film heat transfer is different at the heated and cooled ends. Meanwhile, the heat transfer rate increases with decreasing cross-section area or increasing microcavity length. Comparison of the heat transfer rates under two definitions of thin film region demonstrates that both of them can efficiently ensure the effectiveness of heat transfer characterization, which allows thorough understanding of thin film profile, temperature distribution, interfacial mass flux, and thin film heat transfer for binary fluids.

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## 1. Introduction

The three-phase contact line for a liquid wetting on a solid surface at which the solid, liquid and gas phases intersect can be divided into regions of the adsorbed layer, the thin liquid film and the intrinsic meniscus, based on the meniscus size and the nature of the forces enforcing on the liquid. It was suggested that most of the heat is transferred from 30% of the interface close to the contact line, although further confirmation of it is necessary [1–3]. Nevertheless, studying the heat transfer in the thin liquid film is critical for understanding the heat transfer in the contact line region. In industrial applications of heat transfer engineering such as bubble nucleation during boiling, drop evaporation, liquid film wetting and micro heat pipe, the importance of the thin liquid film is also well known.

Theory based on the concept of disjoining pressure inside the thin liquid film was proposed by Derjaguin and Churaev [4] to account for the pressure which opposes its thinning. Since then intensive theoretical and experimental investigations have been conducted for the thin films of water, diluted salt solutions,

nonpolar liquids, aqueous surfactants, polymer solutions, etc. Some models have been developed to study on the heat transfer characteristics in thin liquid film, considering the effects of thin film profile [5], non-isothermal interfacial conditions [6], liquid polarity [7], thermocapillary convection [8,9] and system size [10]. These effects are inherently related since, for instance, the thin film profile and the non-isothermal interfacial conditions may induce temperature gradient through heat conduction in the film and non-uniform evaporation at the interface. Meanwhile, the temperature gradient along the thin film region results in a thermocapillary convection which reduces the liquid flow towards the high-mass-flux evaporation region and thereby produces thin film instability in the contact line region and unstable startup operation of phase-change devices.

Binary fluids with a less volatile component was suggested to be used for counteracting the thermocapillary convection and delaying the onset of thin film instability through the solutocapillary convection [11]. Thereafter a series of works have been extensively conducted experimentally or theoretically on using binary fluids. For example, Parks and Wayner [12] developed a model for evaporation of binary fluid near the contact line region and obtained the temperature and concentration distributions in the meniscus. The important role of concentration gradient was

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**Nomenclature**

$A$	dispersion constant (J)	$T$	temperature ( $^{\circ}\text{C}$ )
$Ca$	capillary number	$u$	characteristic velocity ( $\text{m}\cdot\text{s}^{-1}$ )
$E$	apparent energy with the zero defined at 298.15 K ( $\text{J}\cdot\text{kg}^{-1}$ )	$V$	volume ( $\text{m}^{-3}$ )
$g$	gravity acceleration ( $\text{m}\cdot\text{s}^{-2}$ )	<i>Greek symbols</i>	
$h_{fg}$	latent heat of evaporation ( $\text{J}\cdot\text{kg}^{-1}$ )	$\alpha$	thermal diffusivity ( $\text{m}^2\cdot\text{s}^{-1}$ )
$k$	thermal conductivity ( $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ )	$\delta$	liquid layer thickness (m)
$L$	characteristic length (m)	$\delta_0$	non-evaporating layer thickness (m)
$m'$	mass flow rate ( $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ )	$\mu$	dynamic viscosity ( $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ )
$m''$	interfacial net mass flux ( $\text{kg}\cdot\text{c}$ )	$\nu$	kinematic viscosity ( $\text{m}^2\cdot\text{s}^{-1}$ )
$\bar{M}$	molecular weight ( $\text{kg}\cdot\text{mol}^{-1}$ )	$\rho$	density ( $\text{kg}\cdot\text{m}^{-3}$ )
$Ma$	Marangoni number	$\sigma$	surface tension coefficient ( $\text{N}\cdot\text{m}^{-1}$ )
$P_c$	capillary pressure ( $\text{N}\cdot\text{m}^{-2}$ )	$\hat{\sigma}$	accommodation coefficient
$P_d$	disjoining pressure ( $\text{N}\cdot\text{m}^{-2}$ )	<i>Subscripts</i>	
$P_l$	liquid pressure ( $\text{N}\cdot\text{m}^{-2}$ )	$c$	cold wall
$P_{sat}$	saturation pressure ( $\text{N}\cdot\text{m}^{-2}$ )	$f$	thin film
$P_v$	vapor pressure ( $\text{N}\cdot\text{m}^{-2}$ )	$h$	hot wall
$P_{v\_equ}$	equilibrium pressure ( $\text{N}\cdot\text{m}^{-2}$ )	$l$	liquid
$q$	heat flow rate ( $\text{W}\cdot\text{m}^{-2}$ )	$ref$	reference state
$Q_{total}$	total heat transfer ( $\text{W}\cdot\text{m}^{-1}$ )	$sat$	saturated
$R$	meniscus radius (m)	$t$	total
$\bar{R}$	universal gas constant ( $\text{J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$ )	$v$	vapor
$S_e$	source term due to heat transfer ( $\text{J}\cdot\text{m}^{-3}$ )		
$S_m$	source term due to mass transfer ( $\text{kg}\cdot\text{m}^{-3}\cdot\text{s}^{-1}$ )		

identified as the major contributor to the mass flux. However, it needs to include the effect of thin film profile on the computation. Kern et al. [13,14] developed a theoretical model for the heat and mass transfer in the thin liquid film of binary mixture and combined the results with macroscopic solution for the liquid and solid domains. Their results demonstrated that the heat transfer in the thin liquid film had a strong influence on the overall heat transfer rate. Recently, Wee et al. [15] developed a comprehensive model to simultaneously calculate all thermophysical properties as well as the thin film profile and investigated the effect of a binary fluid on the heat and mass transfer in an evaporating meniscus. Also, there are many experimental works on the contact line region were explored using various optical and thermal measurement techniques [16]. However, further investigation need to be conducted under conditions that are more comprehensive, including heat transfer for fluid mixtures where the intermolecular interaction between the liquid and the substrate is significantly different.

Self-rewetting fluids, which are aqueous solutions of alcohols with high carbon numbers, are binary fluids with unique surface tension which increases with increasing temperature if it is sufficiently high. These fluids have been used for promoting the fluid flow back to the heated surface and enhancing the heat transfer with an inverted thermocapillary convection in porous structures [17] and devices such as heat pipe [18,19]. In this work, we use a self-rewetting fluid, namely aqueous *n*-butanol solution, to numerically investigate the heat transfer characteristics in the thin film region of closed microcavity, based on an enhanced Young-Laplace equation that includes the contribution of disjoining pressure for binary fluids. Besides the effects of fluid properties and system geometry on the thin film heat transfer, the influence of non-condensable gas in the confined geometries will also be considered, since the composition of gas phase plays an important role in the transport of mass, momentum and energy [20–22]. The developed analysis allows comprehension of thin film profile, interfacial temperature distribution, mass flux distributions at the interface, and contribution of the thin film region to the total heat transfer rate for self-rewetting binary fluid.

**2. Numerical modeling**

The numerical modeling employs the pressure-based finite volume scheme in the Fluent software package. The Simple algorithm is chosen for the coupling of pressure and velocity, and the upwind scheme with second order accuracy is adopted for the discretization of the momentum and energy equations. The schematic diagram and coordinate system for evaporating thin film and intrinsic meniscus regions in a closed microcavity are shown in Fig. 1, where about one third of the space is filled with liquid below the vapor domain. The left wall is the heated end with initial temperature  $T_h = 333.00\text{ K}$ , while the right wall is the cooled end with initial temperature  $T_c = 323.00\text{ K}$ . The temperature of the other walls is  $T_w = (T_h + T_c)/2$ , and the superheat is defined as  $\Delta T = T_h - T_{sat}$ , where  $T_{sat}$  is the saturation temperature of the vapor phase. The conjugate heat transfer includes the thin film and the intrinsic meniscus regions in closed microcavities with different sizes, e.g.,  $40 \times 8 \times 8$ ,  $20 \times 4 \times 4$  and  $5 \times 1 \times 1\ \mu\text{m}^3$ .

The theoretical basis of the modeling is the governing equations used for describing the thin film profile. It is known that the Young-Laplace equation can be used to describe the pressure difference between the vapor and liquid phases at a curved phase interface:

$$P_v - P_l = \sigma K \quad (1)$$

where  $P_v$  and  $P_l$  are the pressures in the vapor and liquid phases, respectively,  $\sigma$  is the surface tension, and  $K$  is the curvature of the liquid-vapor interface. In the case of micro region of a spherical bubble, the interfacial curvature can be expressed as [6]

$$K = \delta''(1 + \delta'^2)^{-1.5} \quad (2)$$

where  $\delta$  is the thin film thickness, and  $\delta'$  and  $\delta''$  are the first and second derivatives of thickness with respect to the film length, respectively. This equation holds for the Gibbs assumption of a two-dimensional phase interface which is not affected by the vicinity of the other interfaces.

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