



# A numerical investigation on the conjugate heat transfer of thin liquid film of water in closed microcavity

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## ARTICLE INFO

### Keywords:

Thin film  
Conjugate heat transfer  
Geometry  
Superheat  
Wettability

## ABSTRACT

The understanding of the conjugate heat transfer in an evaporating thin-film and an intrinsic meniscus is important for enhancing the thermal performance of phase-change heat transfer devices. In this paper, we numerically investigated the conjugate heat transfer in the thin film and the intrinsic meniscus under their own vapor in closed microcavities with different geometries. The results show that, with decreasing microcavity size, the percentage contribution of the thin liquid film to the overall heat transfer increases obviously. However, in order to optimally utilize the thin-film heat transfer, both the microcavity size and the length-height ratio need to be concerned for their effects on the thin-film contribution to the net heat transfer. With increasing superheats that are smaller than 5 K, the contribution of the thin film to the net heat transfer rate becomes somewhat smaller, although the variation seems to be less sensitive to the superheat than the microcavity size. Meanwhile, when the wettability improves, the contribution of the thin film to the net heat transfer rate increases, but the variation of the thin-film contribution is relatively less sensitive to the wettability than the microcavity size and the superheat.

## 1. Introduction

Micro heat pipes have been widely used in industries such as thermal management of microelectronics, radar systems, microgravity and space craft environments, because of its high heat transfer performance and great benefit of energy saving by utilizing latent heat of phase change without external power. However, the understanding of the interfacial phenomena and the heat transfer characteristics of the thin film region in micro heat pipes need to be investigated in detail. The theoretical and numerical studies on thin films have been conducted for decades since Derjaguin et al. [1] introduced the concept of disjoining pressure as the difference between the pressure in a region of a phase adjacent to a surface confining it and the pressure in the bulk of this phase, which arises from an attractive interaction between the two surfaces. Wayner et al. [2] obtained an augmented Young-Laplace equation to balance the forces on the thin film and discussed the evaporating suppression effect of disjoining pressure. Many mathematical models have been proposed to investigate the characteristics of the thin film and the intrinsic meniscus, including the thin-film profile, interfacial temperature, heat flux distribution and mass flow rate. In the literature, some models have been developed using the augmented

Young-Laplace equation and the kinetic theory with different assumptions in the thin-film region [3–8]. Investigations on the factors that may affect the heat transfer and flow pattern in the thin-film region have been conducted. The effects of the superheat, sizes, wick structures, thermal properties, liquid polarity, slip boundary conditions, binary liquids, and Marangoni effect, were taken into consideration [9–19]. However, a few [20] neglect the contribution of the thin film and study the heat transfer and flow pattern of the meniscus.

For small scales, although there are some numerical and experimental studies that involve unsteady and conjugate heat transfer in film flows [21] or other related flows [22–24], the one-dimension characteristics and the profile uncertainty of the thin film make it quite difficult for conjugating modeling with the macro meniscus region and hard to obtain the contribution of the thin film to the total heat transfer. Du et al. [25] proposed a conjugate heat transfer model which includes the evaporating thin film, the substrate and the intrinsic liquid, but they did not consider the contribution of the thin film and treated the shape of evaporating thin-film as a fixed one. Wang et al. [10] developed a complete expression for mass transport across the liquid-vapor interface and studied the contribution of thin film in a microchannel with height equals to the asymptotic intrinsic meniscus diameter. A few consider

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Nomenclature		$S_e$	source term due to heat transfer ( $\text{J}\cdot\text{m}^{-3}$ )
$A$	dispersion constant (J)	$S_m$	source term due to mass transfer ( $\text{kg}\cdot\text{m}^{-3}\cdot\text{s}^{-1}$ )
$E$	apparent energy with the zero defined at 298.15 K ( $\text{J}\cdot\text{kg}^{-1}$ )	<i>Greek symbols</i>	
$g$	gravity acceleration ( $\text{m}\cdot\text{s}^{-2}$ )	$\delta$	liquid layer thickness (m)
$h_{fg}$	latent heat of evaporation ( $\text{J}\cdot\text{kg}^{-1}$ )	$\delta_0$	non-evaporating layer thickness (m)
$k$	thermal conductivity ( $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ )	$\mu$	dynamic viscosity ( $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ )
$m'$	mass flow rate ( $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ )	$\nu$	kinematic viscosity ( $\text{m}^2\cdot\text{s}^{-1}$ )
$m''$	interfacial net mass flux ( $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ )	$\rho$	density ( $\text{kg}\cdot\text{m}^{-3}$ )
$\bar{M}$	molecular weight ( $\text{kg}\cdot\text{mol}^{-1}$ )	$\sigma$	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 ( $\text{N}\cdot\text{m}^{-2}$ )	$h$	hot wall
$P_v$	vapor pressure ( $\text{N}\cdot\text{m}^{-2}$ )	$l$	liquid
$P_{v, equ}$	equilibrium pressure ( $\text{N}\cdot\text{m}^{-2}$ )	$ref$	reference state
$q$	heat flow rate ( $\text{W}\cdot\text{m}^{-2}$ )	$sat$	saturated
$Q_{total}$	total heat transfer ( $\text{W}\cdot\text{m}^{-1}$ )	$v$	vapor
$R$	meniscus radius (m)		
$\bar{R}$	universal gas constant ( $\text{J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$ )		

the fluid flow in evaporation from liquid-vapor meniscus [26], but most of the studies neglected the fact that removing most of the air from a closed cavity can significantly alter the flow structure [27,28]. To address this deficit, the conjugate heat transfer of thin film in a sealed microcavity with pure vapor (no air) need to be further investigated.

Based on our previous work [29], we improve the theoretical model to study the conjugate heat transfer of the evaporating thin liquid film and the intrinsic meniscus under their own vapors in closed microcavities with different superheats, sizes and substrate wettabilities by considering the evaporation and condensation at the interface, liquid and vapor domains. It is expected that this can further help understand the mechanisms influencing the heat transfer in the thin film and improve the performance of phase-change heat transfer devices by using the model.

## 2. Theoretical model

### 2.1. Thin-film modeling

The basis for modeling of the conjugate heat transfer of an evaporating thin liquid film in a closed microcavity is the governing equations employed widely in the literature [2–5] as described below. The augmented Young-Laplace equation describes that the pressure jump between vapor and liquid at the liquid-vapor interface,  $P_v - P_l$ , is induced by both capillary and disjoining pressures:

$$P_v = P_l + P_c + P_d \quad (1)$$

For a non-polar liquid, the disjoining pressure can be expressed as

$$P_d = -\frac{A}{\delta^3} \quad (2)$$

where  $A$  is the dispersion constant and  $\delta$  is the film thickness. The capillary pressure is

$$P_c = \sigma K \quad (3)$$

$$K = \delta''(1 + \delta'^2)^{-1.5} \quad (4)$$

where  $\sigma$  is the surface tension coefficient,  $K$  is the interfacial curvature, and  $\delta'$  and  $\delta''$  are the first and second derivatives of the thickness with respect to the film length  $x$ , respectively. Assuming uniform vapor pressure distribution along the meniscus, the following third-order differential equation can be obtained for the thin-film profile  $\delta(x)$  as combining Eqs. (1)–(4) and differentiating with respect to  $x$ :

$$\delta''' - \frac{3\delta'\delta''^2}{1 + \delta'^2} + \frac{1}{\sigma} \left( \frac{dP_l}{dx} - \frac{3A}{\delta^4} \delta' \right) (1 + \delta'^2)^{1.5} = 0 \quad (5)$$

In the thin-film region, the Reynolds number is usually very low and its length-to-height ratio is large, thus the lubrication theory can be employed to obtain the pressure gradient  $dP_l/dx$  for calculating the mass flow rate  $m''$ :

$$\frac{dP_l}{dx} = \frac{3\nu}{\delta^3} \int_{-\infty}^x m'' dx \quad (6)$$

where  $\nu$  is the kinematic viscosity. Using the extended Clapeyron equation, a simplified evaporation model was proposed based on the kinetic theory for evaporation at the liquid-vapor interfaces, with the net mass flux being [2]:

$$m'' = a(T_v - T_v) - b(P_d + P_c) \quad (7)$$

$$a = C \left( \frac{\bar{M}}{2\pi\bar{R}T_v} \right)^{1/2} \frac{P_v \bar{M} h_{fg}}{\bar{R} T_v T_v}, b = C \left( \frac{\bar{M}}{2\pi\bar{R}T_v} \right)^{1/2} \frac{V_l P_v}{\bar{R} T_v} \quad (8)$$

where  $P_v$  is the bulk vapor pressure at the temperature  $T_v$ .

### 2.2. Governing equations in liquid and vapor domains

As mentioned above, the shape of the liquid-vapor interface is governed by the VOF model due to small scales and high-order nonlinear governing differential equations of the thin film. The VOF model is used with source terms added by user defined functions (UDF) due to mass transfer in multiphase flows. In the VOF model, the tracking of the interface(s) between the phases is accomplished by the solution of a continuity equation for the volume fraction of one (or more) of the phases. For the liquid and vapor phases, these equations are

$$\frac{\partial \alpha_l}{\partial t} + \nabla \cdot (\mathbf{v} \alpha_l) = -\frac{S_m}{\rho_l} \quad (9)$$

$$\frac{\partial \alpha_v}{\partial t} + \nabla \cdot (\mathbf{v} \alpha_v) = -\frac{S_m}{\rho_v} \quad (10)$$

where  $\mathbf{v}$  is the velocity vector,  $S_m$  is the source term due to the mass transfer,  $t$  is the time,  $\alpha_l$  and  $\alpha_v$  are the volume fractions of the liquid and vapor phases, and  $\rho_l$  and  $\rho_v$  are the densities of the liquid and vapor phases, respectively. Volume fractions of all phases sum to unity, or

$$\alpha_l + \alpha_v = 1 \quad (11)$$

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