



# Numerical investigation on conjugate heat transfer of evaporating thin film in a sessile droplet



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## ARTICLE INFO

### Article history:

Received 28 February 2016

Accepted 1 May 2016

### Keywords:

Evaporation

Thin film

Droplet

Conjugate heat transfer

Radius

## ABSTRACT

The conjugate heat transfer in the evaporating thin films of sessile water droplets with different radii ( $R = 0.0707$ ,  $0.1414$ , and  $0.707$  mm, respectively) is numerically investigated based on an augmented Young–Laplace model and the kinetic theory-based expression for mass transport across a liquid–vapor interface by considering the evaporation at the liquid–vapor interface, vapor transport in air, and the liquid domain. The results show that the percentage contribution of the thin film region to the overall heat transfer increases significantly with decreasing droplet size. The thin film contribution becomes somewhat smaller when increasing the superheats that are smaller than 10 K, although the variation of the thin film contribution seems to be less sensitive to superheat than droplet size. Meanwhile, the thin film contribution increases when the surface wettability improves, and its variation is relatively less sensitive to wettability than both droplet size and superheat. This work is helpful for further understanding of the mechanisms influencing the heat transfer in the thin films of liquid droplets.

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## 1. Introduction

As an important transport phenomenon, droplet evaporation has been extensively investigated during the last few decades for its significance in heat transfer enhancement and various applications, such as spray cooling [1,2], controlled deposition [3,4], etc. The physical mechanisms of this phenomenon are critical for these applications involving droplet evaporation processes. However, a comprehensive understanding of them requires the knowledge of the vapor diffusion in the gas phase, natural convection in the gas phase, convection in the liquid phase, evaporative cooling at the liquid–gas interface, and even the conduction in the substrate. For example, vapor diffusion models were widely used for predicting the evaporation characteristics of sessile or suspending droplets, considering the effect of substrate wettability [5–7] and thermal properties [8,9]. Evaporative cooling at the interface and the induced convection in both liquid and gas phases were also extensively investigated for the effects of fluid properties on the evaporation characteristics [10–12]. Natural convection in the gas phase can be important especially when the effect of the substrate heating was taken into account [13–15]. The transport

mechanisms in the contact region was studied in detail since large heat flows may occur near the intersection of a liquid–vapor interface with a solid of an evaporating meniscus [16–18] or confined vapor bubbles [19]. Due to the complexity of the evaporation process of a droplet, transport mechanisms that include vapor diffusion, evaporative cooling, fluid convection, and heat transfer near the triple line, need to be considered comprehensively, and efforts can be found in the literature that incorporate either some of or all of the mechanisms [20–22]. Although many previous investigations have been targeted the understanding of specific droplet evaporation processes, the details of transport are still not fully understood, especially for the comprehensive understanding of the conjugate heat transfer near the triple line during evaporation of water droplet.

The region near the triple line, or the extended meniscus region, was believed to be the main contributor to the heat and mass transfer process for many cases [23]. Categorized by the local thickness and the curvature, the contact region can usually be divided into regions of adsorption layer, evaporating thin liquid film, and intrinsic meniscus. The thin film region which connects the adsorption layer and the intrinsic meniscus was expected that high heat transfer coefficient can be obtained due to the very low thermal resistance in this specific region. Theoretical and experimental researches on this region have also been conducted to investigate the characteristics of it, especially on the thin film

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**Nomenclature**

$a$	proportional constant in Eq. (7b)	$T$	temperature (K)
$A$	area (m <sup>2</sup> ) Hamaker constant (J)	$x$	length along the film (m)
$b$	proportional constant in Eq. (7b)		
$C$	molar concentration (mol m <sup>-3</sup> ) proportional constant in Eq. (7b)	<b>Greek symbols</b>	
$D$	diffusion coefficient (m <sup>2</sup> s <sup>-1</sup> )	$\alpha$	volume fraction
$E$	apparent energy (J kg <sup>-1</sup> )	$\delta$	liquid film thickness (m)
$F$	volumetric force (N)	$\delta_0$	non-evaporating layer thickness (m)
$g$	gravity acceleration (m s <sup>-2</sup> )	$\mu$	dynamic viscosity (kg m <sup>-1</sup> s <sup>-1</sup> )
$h_{fg}$	latent heat of evaporation (J kg <sup>-1</sup> )	$\nu$	kinematic viscosity (m <sup>2</sup> s <sup>-1</sup> )
$k$	thermal conductivity (W m <sup>-1</sup> K <sup>-1</sup> )	$\theta$	contact angle (°)
$K$	interfacial curvature (m <sup>-1</sup> )	$\rho$	density (kg m <sup>-3</sup> )
$m'$	mass flow rate (kg m <sup>-1</sup> s <sup>-1</sup> )	$\sigma$	surface tension coefficient (N m <sup>-1</sup> )
$m''$	interfacial net mass flux (kg m <sup>-2</sup> s <sup>-1</sup> )	$\tilde{\sigma}$	accommodation coefficient
$\bar{M}$	molecular weight (kg·mol <sup>-1</sup> )		
$\mathbf{n}$	unit normal vector	<b>Subscripts</b>	
$p$	pressure (N m <sup>-2</sup> )	air	air
$P_c$	capillary pressure (N m <sup>-2</sup> )	atm	atmosphere
$P_d$	disjoining pressure (N m <sup>-2</sup> )	cell	cell
$P_l$	liquid pressure (N m <sup>-2</sup> )	diff	diffusion
$P_{sat}$	saturation pressure (N m <sup>-2</sup> )	$f$	cell interface
$P_v$	vapor pressure (N m <sup>-2</sup> )	$g$	gas
$P_{v\_equ}$	equilibrium pressure (N m <sup>-2</sup> )	$l$	liquid
$q$	heat flow rate (W m <sup>-2</sup> )	lv	interface
$Q$	cumulative heat transfer (W m <sup>-1</sup> )	net	net value
$r$	contact radius (m)	ref	reference state
$R$	droplet radius (m)	sat	saturated
$\bar{R}$	universal gas constant (J mol <sup>-1</sup> K <sup>-1</sup> )	total	total value
$S_e$	source term due to heat transfer (J m <sup>-3</sup> )	$v$	vapor
$S_m$	source term due to mass transfer (kg m <sup>-3</sup> s <sup>-1</sup> )	$w$	wall
$\mathbf{t}$	unit tangential vector		

profile [23] and its impact on the heat transfer coefficient [24,25], with particular consideration of the effects of superheat [26], geometric sizes [23,27,28], liquid polarity [29], and liquid properties [30,31]. Although investigations on the droplet evaporation and in the thin film region have been performed extensively, the study on the conjugate heat transfer in the thin liquid film of a droplet is rare. In fact, the contribution of a thin liquid film to the overall heat transfer of a curved liquid–gas interface is substantially high when the geometric size is of the same order of magnitude of the thin film thickness. For instance, the ratio of the thin film heat transfer rate to net heat transfer rate is 20% for a microchannel with height of 5  $\mu\text{m}$  and the ratio increases drastically when the geometric size becomes smaller [23]. It is therefore interesting how the thin film influence the heat transfer in the case of droplet evaporation.

Experimental and numerical studies on the evaporation of droplet with volume of the orders of micro-, nano-, and pico-liters (or diameters of about 1000, 100, and 10  $\mu\text{m}$ , respectively), can be found in the literature [19,32,33]. These investigations, however, did not consider the size effect on the thin liquid film, from which the contribution to the total heat transfer should be significant when scales down. In this paper, we introduce a comprehensive model to describe the conjugate heat transfer in the evaporating thin films of sessile water droplets by considering the evaporation at the liquid–vapor interface, vapor transport in air and liquid domains, with particular focus on the effects of droplet radius, superheat and surface wettability. It is expected that this work can further help understand the mechanisms influencing the heat transfer in the thin liquid film and improve the performance of phase-change heat transfer devices involving droplet evaporation by using the model.

**2. Theoretical model****2.1. Thin-film modeling**

Here an evaporating thin film of a water droplet is investigated. The basis for the modeling of the evaporating thin liquid film is the governing equations employed widely in the literature [23–25,34] as described below.

An 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 [24]:

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

The disjoining pressure can be expressed as [18,24,35]:

$$P_d = -\frac{A}{6\pi\delta^3}, \quad (2)$$

where  $A$  is the Hamaker constant and  $\delta$  is the film thickness. There is a minus sign in Eq. (2) such that  $P_d$  is positive only if  $A$  is negative. The Hamaker constants of silicon–silicon ( $A_{11}$ ), water–water ( $A_{33}$ ) and gas–gas ( $A_{22}$ ) are  $18 \times 10^{-20}$  J,  $3.7 \times 10^{-20}$  J, and 0 J, respectively [36]. Using the calculation equation:

$$A_{132} \approx \left(\sqrt{A_{11}} - \sqrt{A_{33}}\right)\left(\sqrt{A_{22}} - \sqrt{A_{33}}\right), \quad (3)$$

the Hamaker constant for the water–silicon–air system becomes  $-4.84 \times 10^{-20}$  J. The disjoining pressure is therefore a positive value, which will push the liquid surface into a convex profile. The capillary pressure is:

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