Internal flow in evaporating droplet on heated solid surface

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ABSTRACT

This work numerically studies the evaporation process of a liquid droplet on a heated solid surface using a comprehensive model. The internal flow within the evaporating liquid droplet is elucidated, while considering the effects of buoyancy force, thermocapillary force, and viscous resistance. The evaporation process is modeled by simultaneously solving the Navier–Stokes equations and energy equation for the liquid domain and the heat conduction equation for the solid domain, while assuming the liquid–vapor interface is a free surface. Three dimensionless parameters are utilized to describe the contribution of individual driving forces to internal flow. Evolutions of the thermal and internal flows during evaporation are discussed. The volume evolution and experimental data are in good agreement.

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1. Introduction

Droplet evaporation is common in conventional and high-tech processes such as metallurgy, nuclear thermal management, and the cooling of microelectronic packages. Extensive experimental efforts have been devoted to elucidating the droplet evaporation process and heat transfer rate on a heated solid surface [1–16]. Theoretical and numerical models have been also developed for estimating evaporation rates of droplets on a heated surface [17–22].

Early models considered the contribution of heat conduction to droplet evaporation, but ignored solid–droplet heat interactions [17,18]. Seki et al. [19] developed the concept of solid–liquid contact temperature, who assumed the solid–liquid interfacial temperature reaches a constant value roughly equal to the interfacial temperature of two semi-infinite solids, developed the concept of solid–liquid contact temperature. di Marzo and Evans [17] adopted the assumption by Seki et al. [19] as the boundary condition when developing the conduction equation within the droplet domain. Makino et al. [20–22] experimentally demonstrated that this assumption is valid only for heated surfaces with high thermal conductivity. Since solid–liquid heat interactions markedly affect droplet evaporation characteristics on a heated surface with low or moderate solid thermal conductivity, research has focused on developing a model

for solid–liquid conjugate heat transfer for evaporating droplets [23–25]. Sadhal and Plesset [23] solved steady-state conjugate heat conduction equations for spherical evaporating droplets and that for an underneath semi-infinite solid surface, while considering the effects of solid properties and the contact angle. The overall heat transfer coefficient at the liquid–vapor interface (free surface) was acquired by exact and approximate schemes. Rizza [24] developed numerical solutions to the solid–liquid conjugate heat conduction equations under constant temperature at the liquid–vapor interface to calculate evaporation time of an impacted disk-shaped droplet. Chandra et al. [25] demonstrated that, when using the conjugate heat conduction model, the decrease in the contact angle significantly reduced evaporation time and enhanced surface cooling. Dunn et al. [26] reported the strong influence of the thermal conductivity of the substrate on the evaporation of a pinned droplet by experiment.

Phase change, which occurs at the liquid–vapor interface, should be considered as the boundary condition when modeling droplet evaporation. The evaporating liquid–vapor interface can be modeled as follows: (i) by correlating the mass transfer coefficient h_c with convective heat transfer h_{conv} using the Chliton–Colburn analogy [27] as $m''_{evp} = h_c(c_i - c_\infty)$, where c_i is vapor concentration at the liquid–vapor interface, and c_∞ is the vapor concentration in the bulk [18,19,26,28]; and (ii) by using the Hertz–Knudsen formula [29,30] to correlate the local vaporization rate with the local thermal environment [31–33]; or (iii) by applying the Fick's law to estimate the evaporation rate of free surface [31,33]. Experimental data also demonstrated that the internal flow field may affect droplet evaporation rates [34–40]. Ruiz and Black [28], in numerically

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Nomenclature

a	thermal diffusivity ($m^2\,s^{-1}$)		V	droplet volume (m^3)
$\overline{A}$	2D volume of the droplet (m^2)		z, r	z-coordinate and r-coordinate (m)
Bi	Biot number			
Bo	Bond number		*Greek symbols*	
f_v	vapor friction factor		θ	contact angle (°)
g	gravity acceleration ($m\,s^{-2}$)		β	volume expansion coefficient of liquid (K^{-1})
Gr	Grashoff number		Δ	difference (–)
h_a	heat transfer coefficient for the non-wetted area ($W\,m^{-2}\,K^{-1}$)		λ	thermal accommodation coefficient (–)
h'_a	comprehensive heat transfer coefficient		μ	dynamic viscosity ($N\,s\,m^{-2}$)
h_c	mass transfer coefficient ($kg\,m^{-2}\,K^{-1}$)		v	kinetic viscosity ($m^2\,s^{-1}$)
h_{conv}	convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)		ρ	density ($kg\,m^{-3}$)
h_{fg}	latent heat of evaporation (J/kg)		σ	surface tension ($N\,m^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)		τ	shear stress ($N\,m^{-2}$)
L	characteristic length (m)			
m''_{evp}	evaporative mass flux ($kg\,s^{-1}\,m^{-2}$)		*Subscripts*	
Ma	Marangoni number		0	initial stage or environment
r	radius (m)		a	air
R	wetting radius (m)		i	liquid–vapor interface
p	pressure (Pa)		l	liquid
q''	heat flux ($W\,m^{-2}$)		sat	saturation
T	temperature (K)		v	vapor
t	evaporation time (s)		w	wall
u	velocity along x-direction ($m\,s^{-1}$)		s	solid
$\vec{V}_l$	velocity vector ($m\,s^{-1}$)		∞	far-field

analyzing the droplet evaporation process while considering thermocapillary convection, neglected natural convection within a droplet. An assumed constant solid–liquid conjugate temperature was valid for a highly thermal conductive heating solid surface. The theoretical results obtained by Ruiz and Black indicated that outcomes from models considering or ignoring the effects of internal droplet flows differed significantly. Savico et al. [38] investigated the Marangoni and buoyant flows in a hanging evaporating drop comprised of both water and n-octane, and determined the associated convective velocities and surface temperature distributions. Savico et al., who developed a model that accounts for the presence of Marangoni shear stresses and evaporation cooling at the liquid–air interface, ignored fluid effects induced by the moving surface and deformation of the liquid–air interface, and the solid effects via conjugated heat transfer. Duh and Yang [41] incorporated the effects of internal flow, including thermocapillary flow, buoyant flow, and combined convective flow, into their droplet evaporation models. However, since a fixed geometry without surface deformation effects and solid–liquid conjugated heat transfer effects was considered, the model developed by Duh and Yang is valid only for the initial stage of droplet evaporation. Hu and Larson [42], who numerically approximated the vapor concentration and flow field in a slowly evaporating droplet, identified roughly hyperbolic shapes of streamlines within a droplet, contradicting the nearly circular cell shapes, as determined experimentally [34]. While considering a free moving surface and various liquid–vapor boundary conditions, Strotos et al. [31–33] and Nikolopoulos [43] numerically examined droplet impinging and evaporation processes on a solid surface, with the VOF method to capture the deformation of free surface. However, the effects of internal flows on the droplet evaporation process was not presented in [33,43]. The two internal recirculation region flow pattern was reported by Strotos et al. [31]. They contributed the buoyancy effects to this internal flow within the evaporating droplet. However, many other researchers [7,28,38,44–47] considered the Marangoni effects as the dominant driving force for the internal flow, while buoyancy effects had always been ignored. So the internal flow within the

evaporating droplet remains an open problem. Few literatures, except for [38,41], had presented the basic mechanism of internal flow with consideration of all of the convection effects within the evaporating droplet. Due to the limitations of the model of [38,41], a more comprehensive model has to be proposed to present the basic mechanism of internal flow.

Table 1 lists the numerical models developed for droplet evaporation on a heated solid surface. Most models analyzed the correlation between droplet geometry, evaporation rate, droplet lifetime, and overall heat transfer rates. Few modeling studies developed comprehensive frameworks that incorporate all significant factors, such as droplet internal flows, including buoyancy-induced natural convection, surface tension gradient-induced Marangoni convection, flow pattern evolution during evaporation, and conjugated heat transfer of solids with finite thermal conductivity. This study developed a comprehensive novel droplet evaporation model that accounts for internal flows within a droplet and conjugated liquid–solid heat transfer. The contributions of natural and Marangoni convection to droplet evaporation heat transfer were examined. The evolution of internal flow patterns during the droplet evaporation process was determined using a dynamic mesh scheme. Finally, the effects of solid thermal conductivity on droplet evaporation were demonstrated.

2. Experimental

Fig. 1 shows a schematic diagram of the experimental setup, consisting of a test section, temperature measurement section, and video acquisition section. The test section comprised a horizontal platform, a heating assembly, and copper plates. The sides of the copper plates and copper heater were insulated, and a glass enclosure was employed to minimize convection heat loss. The T-type thermocouples, 0.3 mm in diameter, were utilized to determine the temperature of the copper plate and that at the heater surface; readings were recorded by a Hewlett-Packard (HP) acquisition system (HP 34401a, Palo Alto, CA, USA). The $50 \times 50 \times 3$ mm