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Two-dimensional computational modeling of thin film evaporation

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ABSTRACT

A considerable amount of the evaporation originates from the close vicinity the three-phase contact line in an evaporating extended meniscus due to the low thermal resistance across the ultra thin film. Evaporation taking place within the thin film region is commonly modeled using the uni-directional flow assumption of the liquid following the lubrication approximation. Although the uni-directional flow based models may yield practically reasonable results in terms of the cumulative quantities such as total evaporation rate, the underlying physics of the problem cannot be explained solely by uni-directional flow, especially when the dominant transverse liquid motion is considered near the close proximity of the contact line. The present study develops a solution methodology to enable the solution of steady, incompressible, 2-D conservation of mass and linear momentum equations for the liquid flow in an evaporating thin film. Solution methodology includes the coupling of an uni-directional solver with high precision numerics, a higher order bi-directional spectral element solver and a finite element solver. The novelty of the present study is that steady, 2-D conservation of mass and linear momentum equations are considered in the modeling of thin film evaporation without the exclusion of any terms in the conservation equations.

1. Introduction

Thin film evaporation is the central issue in various natural and technological processes such as perspiration, micro-electronics cooling, nucleate boiling and self-assembly operations [1]. The adjoining region near the contact line where liquid, vapor and solid phases meet, has the maximum evaporation rates within the extended meniscus due to its small thermal resistance.

Three-phase contact line may be present in different geometries such as liquid meniscus in a container, drop of liquid or vapor bubble on a solid substrate [2]. Heat pipes or vapor chambers are the most common examples in which evaporation from liquid meniscus takes place. Liquid is steadily supplied to the evaporating meniscus from the condenser which enables the construction of these self-regulating devices. Evaporation from a drop of liquid, on the other hand, is present when a solid surface is cooled by droplet deposition. Another presence of evaporation from a thin film is seen at intersection of a bubble with a hot solid substrate where thin film forms between solid and the gas-liquid interface.

Modeling of evaporation requires the application of simplifications due to the inherent complexity of the problem. Lubrication theory approximation, which assumes the uni-directional liquid flow, is a common tool to model the liquid flow in evaporating thin films [3–19]. Based on lubrication theory, different physical effects can be investigated. The effect of thermocapillarity increases with elevated superheats and is considered in many studies [20,21]. For certain types of fluids, acute errors can be made by neglecting the thermocapillary effect [22,23]. The effects of slip boundary condition [24,25] and liquid polarity [26] were also investigated in previous studies.

Evaporation modeling with an extended version of the lubrication theory also exists in the literature [27]. Extended version uses a domain perturbation method to develop the higher-order solution in terms of series expansion about lubrication condition. Zeroth and first-order closed-form solutions are taken into consideration. Zeroth-order closed-form reduces formulation to the lubrication theory. First-order closed-form adds the inertial terms of the longitudinal momentum into formulation.

When conservation of mass, linear momentum and energy equations are subjected to an order of magnitude analysis depending on the scaling of the thickness of the absorbed layer as

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Nomenclature

Symbols

A	Dispersion constant, J
A_r	Dispersion constant for retarded films, J
c_p	Specific heat capacity, J/kg·K
h_{lv}	Latent heat of evaporation, J/kg
k	Thermal conductivity, W/m·K
ℓ^*	Extent of the evaporation zone, m
M	Molar mass of liquid, kg/mol
$\dot{m}$	Mass flow rate, kg/s
$\dot{m}'$	Mass flow rate per unit length, kg/m·s
$\dot{m}''$	Mass flux, kg/m^2·s
$\mathbf{n}$	Unit normal vector
p	Pressure, Pa
q''	Heat flux, W/m^2
R	Radius of curvature of liquid-vapor interface, m
R_u	Universal gas constant, J/mol·K
s	Transformed (standard) longitudinal coordinate, m
t	Transformed (standard) transversal coordinate, m
$\mathbf{t}$	Unit tangential vector
T	Temperature, K
$\mathbf{u}$	Velocity vector, m/s
u	Longitudinal velocity, m/s
v	Transversal velocity, m/s
v_g	Specific volume of gas, m^3/kg
v_l	Specific volume of liquid, m^3/kg
V	Molar volume, m^3 /mol
x	Longitudinal coordinate, m
y	Transversal coordinate, m

Greek symbols

δ	Liquid film thickness, m
δ^*	Contact line thickness, m
μ	Dynamic viscosity, kg / m·s
ν	Kinematic viscosity, m^2 /s
Ω	Problem domain, m^2
ρ	Density, kg/m^3
σ	Surface tension, N/m
$\overline{\overline{\sigma}}$	Stress tensor, Pa
$\boldsymbol{\sigma}'$	Deviatoric stress tensor, Pa
$\widehat{\sigma}$	Accommodation coefficient
θ	Apparent contact angle, °

Subscripts

0	inlet of the problem domain
c	capillary
d	disjoining
$evap$	evaporation
l	liquid
lv	liquid-vapor
st	standard
v	vapor
v, lv	vapor just above the liquid-vapor interface
w	wall

the transversal characteristic length and entire length of the thin film region as longitudinal characteristic length, governing equations are reduced to the classic lubrication formulation [27,28]. The scaling analysis yields a much smaller value than unity for the ratio of transverse velocity to longitudinal velocity. Therefore, unidirectional liquid flow is assumed within the thin film region. However, in the close vicinity of the contact line, where the local rate of evaporation is at its peak value, transverse velocity dominates the longitudinal one. To capture the physics of the evaporation problem within the entire domain, bi-directional liquid flow needs to be considered.

The main objective of the current study is to propose a general thin film evaporation model based on bi-directional liquid flow. The solution scheme includes an iteration process which consists of successive implementation of three coupled solvers; unidirectional solver with high precision numerics, higher order bidirectional spectral element solver and finite element solver. The novel contribution of the present study is that steady, 2-D conservation of mass and linear momentum equations for the liquid flow within the thin film are solved to model the evaporation without neglecting any terms.

2. Problem description

A steadily evaporating two-dimensional extended meniscus on a hypothetical perfectly flat heated surface, as illustrated in Fig. 1, is investigated.

Evaporating thin film region is characterized by high evaporation rates due to low thermal resistance of thin film, whereas intrinsic (bulk) meniscus region has high resistance to heat conduction due to thicker film. At the contact line, evaporation is suppressed by dispersion force originating from the solid-liquid molecular interactions. Steady, laminar, incompressible flow of Newtonian, spreading and non-polar liquid is provided from intrinsic meniscus to evaporating thin film region to replace the evaporating liquid in the close vicinity of the contact line. Assuming a sufficiently small Bond number, the effect of gravity is neglected. The heated solid substrate under the liquid film is assumed to have a constant wall temperature. Liquid is assumed to evaporate into its saturated vapor phase which has uniform physical properties. Variation of physical properties with the temperature is neglected within the solution domain. Zero shear stress is assumed at the interface. For the normal stress balance, the effects of capillary and disjoining pressures are considered [29]. Applying these assumptions, two-dimensional conservation of mass, linear momentum and energy equations are as follows:

$$\partial_x u + \partial_y v = 0 \,, \tag{1a}$$

$$\rho\left(u\partial_x u + v\partial_y u\right) = -\partial_x p + \mu\left(\partial_{xx} u + \partial_{yy} u\right) \,, \tag{1b}$$

$$\rho\left(u\partial_x v + v\partial_y v\right) = -\partial_y p + \mu\left(\partial_{xx} v + \partial_{yy} v\right) \,, \tag{1c}$$

$$\rho c_p\left(u\partial_x T + v\partial_y T\right) = k\left(\partial_{xx} T + \partial_{yy} T\right) \,. \tag{1d}$$

The associated boundary conditions with Equations (1a)–(1d) are specified as follows:

$$u = 0, \quad v = 0, \quad T = T_w \quad \text{at} \quad y = 0 \,, \tag{2a}$$