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Evaporation of a thin viscous liquid film sheared by gas in a microchannel

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ABSTRACT

In the present paper a 3D non-stationary two-sided mathematical model of joint motion of evaporating liquid film and cocurrent gas flow in a microchannel with local heating has been developed. This model takes into account a deformable gas–liquid interface, convective heat transfer in the liquid and the gas phases as well as temperature dependence of surface tension and liquid viscosity. Assuming the lubrication theory to be valid, the problem has been reduced to five governing equations for the film thickness, temperature fields in the gas and liquid, vapor concentration in the gas phase and gas pressure. Numerically it is shown that for films sheared by gas in microchannels vapor is transported by forced convection and diffusion, and diffusion plays the most considerable role in vapor transport at low gas velocities. Also, it is shown that concentration and thermal boundary layers are formed. The boundary layers have a specific S-shaped form. The width of the vapor track increases along the gas flow direction in front of the heater and decreases downstream the heater. The distance over which the width decreases is an order of magnitude higher than the heater length. This fact can be explained by the condensation of the vapor.

1. Introduction

The flows of thin fluid films are encountered in condensers, heat-exchangers, microfluidic devices [1], in wetting and spreading [2], in cooling devices, as well as in biomedical and geophysical applications [3]. Over the past decades, numerous theoretical and experimental research works have been focused on the dynamics of thin films driven by various forces such as gas flow, gravity, capillarity, thermocapillarity and intermolecular forces. In these works the film flow over smooth and structured surfaces or surfaces with nonuniform distribution of temperature was considered [4–6]. As well evaporation and condensation processes were taken into account in many studies [7,8]. Lubrication theory has been used widely in the modeling in thin film flows [4,9]. A majority of work has focused on the analysis of a single evolution equation.

Investigation of interfacial flows driven by evaporation has a long history starting from the works of Thomson [10] and Marangoni [11]. The long-scale models for evaporative thin liquid films dealing with the limit of negligible vapor dynamics are summarized in [4]. In more recent works these so-called “one-sided” models [7,12] have been replaced by two-sided models taking into account the dynamics in the vapor [13,14]. Moreover, the boundary conditions at the evaporating interface are complicated. Many works dealing with coupled evaporation and thermocapillary effects assume the liquid to be in contact only with its own vapor [15]. However, experimental and theoretical investigations show that the presence of an additional non-condensable gas component leads to surface-tension-driven instabilities [16]. In many studies liquid film is supposed to be at rest with constant thickness. However, as shown in [17,18], this assumption is justified only for relatively thick film at low evaporation rates. The limiting factor at deformable interface is film rupture at low liquid flow rates. In some works temperature discontinuity at the liquid–gas interface during evaporation is taken into account [17]. However, this effect can be neglected unless the phase change occurs too rapidly or at a relatively low pressure.

The evaporation of droplets has also attracted much interest. As the liquid evaporates, the droplet is either pinned [19] or recedes on a wetting substrate [20]. The effect of substrate thermal resistance on droplet evaporation is studied systematically in [21]. Evaporating droplets also demonstrate instabilities at the contact lines [22], and instabilities occurring due to Marangoni forces

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Nomenclature

$\mathbf{A}$	dimensionless number ($g\cos\alpha H_0^2/U^2 l$)
b	heat transfer coefficient, W/(m^2 K)
c_p	specific heat of the liquid, J/(kg K)
C	mass fraction of moisture in the gas phase
$\mathbf{C}$	inverse Froude number, ($g\sin\alpha H_0/U^2$)
$C_*(T)$	mass fraction of moisture in the gas phase corresponding to the pressure of the saturated vapor at the temperature T
D	diffusion coefficient, m^2/s
$\mathbf{D}$	modified Prandtl number, ($c_p\mu_0 H_0/l\kappa$)
$\mathbf{E}$	dimensionless number, ($f\,H_0^2/\mu_0 U$)
f	the gas pressure gradient in the longitudinal direction, kg/(m^2 s^2)
$\mathbf{g}$	gravitational acceleration vector, m/s^2
h	dimensionless film thickness
H	local film thickness, m
H_c	channel height, m
$i,j,k,$	mesh point at a time step
I	identity tensor
k_1, k_2, k_3	dimensionless coefficients
K	curvature of the interface, 1/m
K_1, K_2	cells number in the calculations
l	characteristic scale of streamwise length, m
L	heater length, m
$\mathbf{L}$	Evaporation number, ($\lambda D\rho_g/\kappa[T]$)
m	number of a time steps in the calculations
$\mathbf{Ma}$	Marangoni number ($\sigma_T[T]H_0^2/Ul\mu_0$)
$\mathbf{n}$	normal unit vector
p	pressure, N/m^2
$\mathbf{P}$	stress tensors
q	heat flux released on the heater, W/m^2
Q	flow rate of the liquid per unit film width, m^2/s
$\mathbf{R}$	modified diffusion Peclet number, ($Dl/H_0^2 U$)
$\mathbf{Re}$	Reynolds number ($\rho Q/\mu$)
S_0	heating area, m^2
$\mathbf{S_g}$	modified Schmidt number, ($\mu_{0g}H_0/D\rho_g$)
T	temperature, °C
$[T]$	characteristic scale of the temperature, K
U	characteristic scale of the liquid velocity, m/s
$\mathbf{v}$	velocity vector
u, v, w	velocity components, m/s
V_n	velocity of the interface in the direction of normal unit vector, m/s
W	rate of strain tensor
x, y, z	Cartesian coordinates, m
Greek symbols	
α	plate inclination angle, °
ε	the film aspect ratio
$\wp$	estimated time of the calculation process, dimensionless
κ	thermal conductivity, W/(m K)
λ	latent heat of vaporization, J/kg
Λ	difference operator in the calculations
μ	liquid dynamic viscosity, kg/(m s)
Π	grid analogue of an unknown function in the calculations
θ	dimensionless temperature of the liquid
ρ	liquid density, kg/m^3
σ	surface tension, N/m
τ	time step
ω	ratio of the channel height to the initial film thickness
Subscripts	
0	initial parameters of the flow (at $T = T_0$)
g	gas phase
x, y, z, T, ξ	derivatives on x, y, z, T and ξ
Superscripts	
1	modified velocity components
_	dimensionless variables

[23]. From the literature, it could be concluded that the effect of convection in the gas phase for drop evaporation is still not completely understood [24,25].

Many authors have considered evaporative effects coupled to other effects, for example lubrication theory has been used to study the stability and dynamics of evaporating films in the presence of surfactants, interfacial viscosity, thermal Marangoni effects, and the disjoining pressure [26]. In this work the effects of various destabilizing mechanisms are compared with each other using the linear stability analysis. In [27] the effects of capillarity, evaporation, conjoining pressure and viscous drug on film evolution have been studied using the lubrication approximation. Evaporating films in the presence of intermolecular forces are studied in [28]. The pattern formation accompanying dewetting of evaporating film on homogeneous and chemically heterogeneous substrates using time-dependant numerical simulations is examined in [29]. Convective heat and mass transfer with evaporation of a falling film in a closed rectangular cavity has been studied in [30]. In [31] the dynamics and stability of a thin, viscous film of volatile liquid flowing under the influence of gravity over a nonuniformly heated substrate has been investigated using lubrication theory. Attention is focused on the regime in which evaporation balances the flow due to gravity. In [18] evaporation effect on heat transfer has been investigated for shear-driven thin liquid film in a channel at local heating. The problem of heat and mass transfer has been examined in the framework of one-dimensional long-wave model. In [32] numerical and theoretical study of evaporative convection in an open cavity under shear stress flow is performed. In [33] investigation of evaporation effect on fingering instabilities for thin viscous liquid film flowing down under the action of gravity is carried out. In [34] the problem of a two-layer system consisting of a horizontal liquid layer in contact with its own vapor is considered. Effects of buoyancy, thermocapillarity, evaporation, and the dynamics of the vapor phase are taken into account. The results show that both the evaporation and the interfacial shear play important roles in the stability of the system. However, combined effects of nonuniform heating, gas dynamics, evaporation and thermocapillarity have been only partially understood for thin viscous liquid film flows. Other important aspects in the study of liquid flows, notably the fundamental aspects of the interfacial conditions, have become important in recent years [32,35]. In [32] boundary conditions between two interacting phases have been presented in general form. These conditions have been derived from strong discontinuity relations for generalized fluid–fluid motions. In [35] the interfacial conditions have been derived from the integral conservation laws of mass, impulse and energy for the evaporating liquid drop in conditions of zero gravity.

In this paper three-dimensional time-dependent two-sided mathematical model has been developed to understand the effects of nonuniform heating, Marangoni effect and evaporation on hydrodynamics and heat transfer in shear-driven liquid films in a microchannel. For a deformable gas–liquid interface convection