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Numerical study of conjugated heat transfer in evaporating thin-films near the contact line

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ABSTRACT

The study of the mechanics of evaporating thin-films is important for improving the performance of phase-change heat transfer equipment. Various factors, including the changing profile of the thin-film with superheating and the use of small-scale and one-dimensional higher-order nonlinear governing differential equations, create difficulties for the study of the conjugated heat transfer of the thin-film and its surrounding regions. In previous studies, models of the conjugated heat transfer are simplified. The shape of the evaporating thin-film is treated as fixed, or the constant substrate temperature (CST) thin-film model is used. In this paper, a full conjugated heat transfer model, including the evaporating thin-film, the near-solid substrate and the intrinsic liquid, is proposed to study the heat transfer characteristics in the contact line region in a micro channel or a micro groove. The results show that a temperature valley value exists on the surface of the solid substrate corresponding to the peak value of the heat flow rate in the thin-film. The apparent contact angle is smaller than that of the CST model. The CST model overestimates the peak and the total heat flow rate, especially when the thermal conductivity k_s of the substrate is low. For convenience in engineering applications, two simplified conjugated models are developed and evaluated by the full model. For low k_s substrates, the simplified models can be used directly. Changing the thickness of the substrates affects the relative errors only slightly.

1. Introduction

Evaporating thin-films play an important role in many phase-change heat transfer equipments due to the extremely low thermal resistance of thin-films. The mechanics of the evaporating thin-films have been studied for decades both theoretically and experimentally. Since the disjoining pressure of Derjaguin et al. [1,2] was introduced into this field, the combined effects of the disjoining pressure, capillary pressure and temperature have been studied. The Kelvin–Clapeyron equation is used to describe the effect of the liquid supply and suppression of the evaporation by the combined forces [3,4]. The augmented Young–Laplace equation is used to describe the pressure jump across the interface [5,6]. Experiments were conducted by Dasgupta et al. to validate the theories with interferometry and ellipsometry [7–9]. The evaporating thin-film theory was extended to more complex geometries by many researchers [10–13]. The slip boundary and vapor pressure gradient have been stressed in Park's models [14,15]. Wang et al. [16] compared the results of the Schrage's evaporation theory [17] and the simplified expressions developed by Wayner and co-workers.

Because the validity of the evaporating thin-film theory is widely accepted, the study of conjugated heat transfer, including the evaporating thin-film, the solid substrate and the intrinsic meniscus, has more practical applications. The effects of heat conduction in the substrate of liquid droplets have been studied by Ajaev [18], Dunn et al. [19,20] and other researchers [21,22]. However, the number of conjugated heat transfer models of the steady state meniscus in a micro channel or a micro groove is limited in the literature. Schonberg et al. [23] studied the heat transfer in the evaporating thin-film region and in the intrinsic meniscus region, but the solid substrate was not included. In the models of Do et al. [24,25], the heat transport properties of an evaporating thin-film in a groove of a flat heat pipe is calculated with a constant substrate temperature (CST) model. Clearly, the CST model overestimates the total heat transfer of the meniscus. Panchamgam et al. [26] conducted a comprehensive experimental and theoretical study. In his study conduction in the solid was included. But it was not a pure numerical result since experimental data forced the solution. It used a combination of experimental data and three complementary models. Wang et al. [27] modeled a volatile meniscus inside an open microtube. Ranjan et al. [28] modeled an evaporating meniscus in four different heat pipe wick structures. However, in their models, the profile of the evaporating thin-film is treated as a fixed-shape, and the wicks are regarded as having

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Nomenclature

A	dispersion constant [J]
b_s	thickness of the solid substrate [μm]
h_{fg}	latent heat of evaporation [J/kg]
h_n	heat transfer coefficient of natural ventilation [W/m^2 k]
k	thermal conductivity [W/m K]
K	interfacial curvature [1/m]
m''	interface net mass flux [kg/m^2 s]
$\overline{M}$	molecular weight [kg/mol]
$\overline{R}$	universal gas constant [J/mol K]
P	pressure [N/m^2]
P_c	capillary pressure [N/m^2]
P_d	disjoining pressure [N/m^2]
P_{v_eqv}	equilibrium vapor pressure [N/m^2]
q	heat flow rate [W/m^2]
q_t	integrated heat flow rate of the evaporating thin-film region [W/m]
Q_t	total heat flow rate of the evaporating meniscus [W/m]
r	radius [m]
R	thermal resistance [m^{2}k/W]
T	temperature [K]
V	molar volume [m^3/mol]
x	x-coordinate [m]
y	y-coordinate [m]

Greek symbols

Γ	mass flow rate [kg/ms]
ε	relative errors of total heat flow rate in the numerical process
δ	liquid layer thickness [m]
δ_0	thickness of the non-evaporating layer, adsorbed layer [m]
μ	dynamic viscosity [Ns/m^2]
ν	kinematics viscosity [m^2/s]
ρ	density [kg/m^3]
σ	surface tension coefficient [N/m]
$\widehat{\sigma}$	accommodation coefficient

Subscripts

c	conjugated model
l	liquid
lv	liquid-vapor interface
max	maximum
ref	reference
s	solid substrate, heater wall
sat	saturation
sf	solid surface connected with liquid part
T	constant substrate temperature (CST) thin-film mode
v	vapor

a constant temperature. Recently, Wang et al. [29] conducted a numerical investigation of heat and mass transfer from an evaporating meniscus. A small temperature valley is obtained at the contact line which is consistent with the experimental observations. But in his model, the thin-film region with the thickness less than 1 μm is not included.

The small scale, uncertainty of the profile and one-dimensional higher order nonlinear governing equation of the thin-film region make it difficult to combine with other regions, which can be described with conventional rules. In this study, we developed a numerical conjugated heat transfer model that can be used when experimental methods are not available. We solve these problems by programming with Matlab and Comsol Multiphysics interactively. In addition, for easy application in engineering fields, two simplified models were developed and evaluated with the full model.

2. Theoretical models

The two-dimensional conjugated heat transfer model includes three parts: the evaporating thin-film, the intrinsic meniscus and the solid substrate, as shown in Fig. 1. The dry-out area, which belongs to the solid substrate, is specified individually. The fluid is supplied through boundary 7 for a micro channel or from the flow perpendicular to the paper plane for a groove. It is designed to model the crucial part of heat transfer process in a phase change heat exchanger. The solid substrate is assumed to be ideally rigid and smooth.

Material properties and system parameters are listed in Table 1.

2.1. Evaporating thin-film region

The evaporating thin-film model used here is obtained from the most widely accepted models in the literature [4,6–9,16,30,31].

A steady-state, completely wetting thin-film at the edge of an evaporating meniscus is investigated. The capillary forces are restricted by constant surface tension. It is assumed that the pressure in the liquid does not vary in the direction perpendicular to the substrate. The liquid-vapor interface temperature is a function of position, and the gas domain is assumed to maintain a constant pressure and consist of a pure and saturated vapor. The effect of gravity is not included.

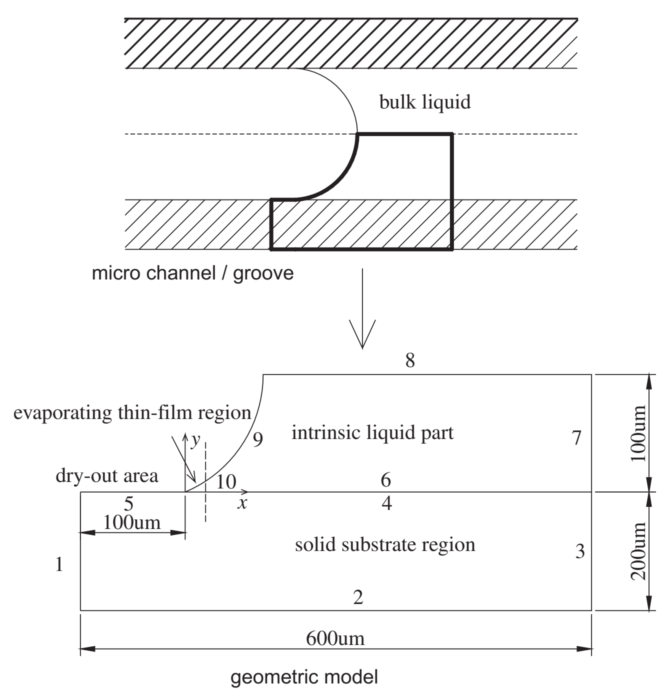

Fig. 1. Schematic diagram of the conjugated heat transfer model. Note: BCs 1, 3, 7, 8 and 10 are insulation boundaries. BCs 2 and 9 are constant temperature boundaries. BC 5 is natural ventilation boundary. BCs 4 and 6 belong to the solid region and intrinsic liquid region separately and are coupled together.