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Numerical investigation of heat and mass transfer from an evaporating meniscus in a heated open groove

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ABSTRACT

The process of evaporation from a meniscus into air is more complicated than in enclosed chambers filled with pure vapor. The vapor pressure at the liquid–gas interface depends on both of the evaporation and the vapor transport in the gas environment. Heat and mass transport from an evaporating meniscus in an open heated V-groove is numerically investigated and the results are compared to experiments. The evaporation is coupled to the vapor transport in the gas domain. Conjugate heat transfer is considered in the solid walls, and the liquid and gas domains. The flow induced in the liquid due to Marangoni effects, as well as natural convection in the gas due to thermal expansivity and vapor concentration gradients are simulated. The calculated evaporation rates are found to agree reasonably well with experimentally measured values. The convection in the gas domain has a significant influence on the overall heat transfer and the wall temperature distribution. The evaporation rate near the contact lines on either end of the meniscus is high. Heat transfer through the thin liquid film near the heated wall is found to be very efficient. A small temperature valley is obtained at the contact line which is consistent with the experimental observation.

1. Introduction

A variety of industrial applications have exploited the high heat transfer rates that can be supported by the phase change occurring in evaporating liquid menisci in capillary structures. A detailed understanding of the heat and mass transfer occurring in evaporation from menisci under different operating conditions is critical to the proper design of a variety of passive phase-change devices.

A V-shaped groove is a type of capillary structure that has been widely studied. In many of the past studies, a closed system was considered in which the vapor domain was assumed to be uniform at saturated conditions, including in the region near the meniscus. Xu and Carey [1] developed an approximate model for meniscus evaporation in a V-groove. They assumed that the liquid flow along the groove was driven primarily by the capillary pressure difference due to the recession of the meniscus towards the apex of the groove. Khrustalev and Faghri [2] presented a mathematical model for the heat transfer through thin liquid films in the evaporator section of heat pipes with capillary grooves. The model accounted for the effects of interfacial thermal resistance, disjoining pressure, and surface roughness for a given meniscus contact angle. An analytical investigation of the heat transfer characteristics of evaporating thin liquid films in V-shaped microgrooves was conducted by Ha and Peterson [3]. The extended meniscus was divided into three regions: absorbed layer or non-evaporating region, evaporating thin film or transition region, and intrinsic meniscus region. Stephan and Busse [4] calculated the heat and mass transfer in the micro-region and then combined the solution with a treatment of the macroscopic meniscus within open grooves. Burelbach et al. [5] conducted a theoretical analysis of evaporating/condensing liquid films, in which vapor recoil and Marangoni convection were included. Schmidt [6] discussed the influence of Marangoni and buoyancy effects on the flow field near an evaporating meniscus. A number of studies [7–10] have also investigated the disjoining pressure due to long-range molecular forces as well as evaporation from the thin liquid film at the contact line.

The transport process is more complicated, however, if the gas domain is not uniformly saturated with vapor but contains non-condensable gases as well. Although evaporation into unsaturated vapor domains is encountered widely in applications, it is less well-understood. Deegan et al. [11] investigated the drying process of water droplets in open space, showing that the evaporation from droplets was influenced by diffusion of vapor in the air. Cachile et al. [12] also investigated droplet drying in air and explained their experimental results by considering vapor transport in air. Dhavaleswarapu et al. [13] used micro-particle image velocimetry

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Nomenclature

A	area (m^2)
C	vapor molar concentration (mol/m^3)
D	diffusion coefficient in air (m^2/s)
Gr	Grashof number
J	molar flux (mol /(m^2 s))
h_{fg}	latent heat of evaporation (J/kg)
k	thermal conductivity (W/(m K))
l	characteristic length (m)
m	mass (kg)
m_{net}	mass flow rate (kg/s)
m''_{net}	mass flux (kg/(m^2 s))
M	molecular weight (kg/mol)
$\bar{M}$	molecular weight (kg/kmol)
n	interface normal coordinate (m)
p	pressure (N/m^2)
R	radius (m)
$\overline{R}$	universal gas constant (J/(mol K))
Re	Reynolds number
T	temperature (K)
t	time (s)
V	fluid velocity (m/s)

Greek symbols

β	thermal expansion coefficient (1/K)
δ	thickness (m)
θ	contact angle
ν	kinematic viscosity (m^2/s)
μ	dynamic viscosity ((N s)/m^2)
ρ	density (kg/m^3)
σ	surface tension coefficient (N/m)
$\overline{\sigma}$	interface accommodation coefficient
τ	shear stress (N/m^2)

Subscript

diff	diffusion
e	evaporation
equ	equilibrium
g	gas (vapor/air mixture)
l	liquid
lv	interface
out	outlet
ref	reference
sat	saturated
v	vapor

to reconstruct velocity fields in sessile water droplets evaporating into air. The spatial and temporal distribution of the local evaporative mass flux was determined, and the temperature distribution in the droplet near the contact line was estimated. Buffone et al. [14,15] conducted experiments on a meniscus in a microtube which was open to air. Similar experiments in [16] delineated Marangoni convection in capillary tubes. More recently, Pan and Wang [17] numerically investigated the broken symmetry of the Marangoni convections in micro-tubes, where a non-uniform vapor diffusion could be with responsibility.

Migliaccio et al. [18] recently conducted detailed experiments for an evaporating heptane meniscus in a V-groove open to air. The groove was made of fused quartz, and electrical heating was provided by a thin layer of titanium coated on the backside of the quartz substrate. The effects of liquid feeding rate on the temperature suppression and meniscus shape were explored. High-resolution infrared thermography was employed to investigate the temperature profile on the groove wall. A small temperature valley was recorded at the contact line, indicating the localized cooling due to thin film heat transfer. The present work reports on a numerical investigation conducted for the evaporating meniscus in the open V-groove under conditions matching those of the experiments in [18]. The evaporation and vapor transport are coupled at the meniscus in the numerical model. The evaporation process, cooling effect and conduction in the groove wall, Marangoni flow, and convection in the vapor are all comprehensively investigated. The predicted results are compared to those from the experiments.

2. Mathematical model

2.1. Problem description

The experiments in [18] considered a V-groove setup consisting of an angled heated quartz wall and a vertical center wall as shown in Fig. 1, simulating one half of a V-groove. The outer surface of the quartz wall is heated by means of electrical power supplied to a thin metallic film deposited on this surface. A meniscus is sustained between the two walls, and its shape is determined by optical means. The half V-groove in the experiments is 50 mm long in the axial (z-) direction. To replace the liquid lost to evaporation, a syringe pump continuously feeds room-temperature liquid to the groove through a capillary tube positioned just above the meniscus contact line, 12.5 mm from one end of the groove. For the present modeling work, the liquid meniscus profile obtained at a liquid supply rate of 6.55×10^{-7} kg/s and an applied heat flux of 1800 W/m^2 is chosen for investigation. A two-dimensional representation of the problem is adopted as shown in Fig. 1, for computational tractability. The mass loss due to evaporation in the liquid is not considered in the model since there is no liquid supply inlet in the 2D representation; this is a reasonable simulation of the experiment since the liquid consumption in the experiment is of order of 1×10^{-5} kg/(s m), with corresponding induced liquid flow velocities of less than 1×10^{-5} m/s.

2.2. Evaporation and vapor transport at the meniscus

The evaporation from a liquid–gas meniscus is determined by several factors. The interfacial temperature T_{lv} is important since a higher T_{lv} brings more higher-energy liquid molecules to cross the interface into the vapor phase. The vapor pressure near the interface p_{v_lv} is also an important factor because a higher p_{v_lv} means that more vapor molecules could cross the interface back into the liquid phase, thus reducing the net evaporation mass flux m''_{net}; evaporation into a vacuum is more intensive than that into a vapor domain. When evaporating into air, the vapor molecules must diffuse through the air under a driving force. Thus, the vapor pressure near the interface p_{v_lv} must be higher than that far from the interface. To be complete, analysis of evaporation at the meniscus must account for vapor transport in the gas domain.

The net evaporated mass flux across the interface may be calculated according to the molecular kinetics-based evaporation theory of Schrage [19]:

$$M''_{net} = \frac{2\overline{\sigma}}{2-\overline{\sigma}}\left(\frac{\overline{M}}{2\pi\overline{R}}\right)^{1/2}\left(\frac{p_{v\_equ}(T_{lv})}{T_{lv}^{1/2}} - \frac{p_{v\_lv}}{T_{v\_lv}^{1/2}}\right) \quad (1)$$