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Experimental study on evaporation of pentane from a heated capillary slot

V.S. Jasvanth [a], Amrit Ambirajan [b,*], Jaywant H. Arakeri [c]

[a] Thermal Systems Group, ISRO Satellite Centre, HAL Airport Road, Bangalore 560017, Karnataka, India
[b] Thermal Systems Group, ISRO Satellite Centre, Bangalore 560017, Karnataka, India
[c] Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560012, India

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ABSTRACT

An experimental investigation of evaporation of a pentane meniscus from a heated capillary slot is presented. A novel aspect of this study is that both the wicking height and steady state evaporation mass flow rate are measured simultaneously. Based on a macroscopic force balance, the apparent contact angle of the evaporating meniscus is experimentally estimated from the wicking height and mass flow rate. This is compared with the results obtained using evaporating thin-film theory. The experimentally estimated contact angle is slightly larger than that obtained from the thin-film model but both show similar trends. Further, it is found that the reduction in the meniscus height is primarily due to an increase in the apparent contact angle. The liquid and vapor pressure drops in the capillary are insignificant relative to the capillary pressure.

1. Introduction

The evaporating liquid–vapor meniscus plays an important role in passive capillary-driven phase change devices like heat pipe, Loop Heat Pipe (LHP) and Pulsating Heat Pipe (PHP). In heat pipes and LHPs, the capillary forces generated in the wick and the evaporation from the liquid–vapor meniscus provide the necessary driving force for circulation of the working fluid through the loop (from the condenser to evaporator). The heat transport capability of these devices depends on the maximum capillary force generated at the evaporating meniscus and on the properties of the working fluid. The wetting characteristics of the evaporating liquid–vapor meniscus with the solid surface is characterized by an apparent contact angle, that affects the maximum capillary pumping ability. Better understanding of the evaporating meniscus within a pore of capillary structure is important for predicting the heat transport capability of these devices. Thus the goal of this paper is to study the evaporation from a pentane meniscus formed in a pore (capillary slot). An experimental investigation is carried out by measuring the wicking height and evaporation mass rate from a heated capillary slot to estimate the apparent contact angle. This is then compared with the contact angle predicted by evaporating thin-film theory.

The evaporation process is considered a multi-scale problem [1] as it combines the micro scale physics near the contact line region (liquid–vapor–solid region) with the macro scale problem of fluid flow in the capillary, driven by evaporation in the meniscus. At the micro scale, the physics near the contact line region of the evaporating thin-film region has been extensively studied both theoretically and experimentally by many investigators. Potash and Wayner [2] and Wayner et al. [3] combined the Kelvin and Clapeyron equations to describe the evaporation process from an evaporating thin film dictated both by disjoining and capillary pressures. Moosman and Hoomsy [4] compared the thin-film profile change relative to the static isothermal profile. The evaporating thin film thickness profile were obtained using ellipsometry and interferometry as a function of evaporation rate and compared with evaporating thin-film theory [5–9]. Pratt et al. [10] speculated that the instabilities in the evaporating thin film could be due to thermocapillary effects. Wang et al. [11] solved for the evaporating thin film profile considering complete expression for mass transport. Hohmann and Stephan [12] and Sodtke et al. [13] measured the wall temperatures of an evaporating meniscus in a capillary slot; and close to micro region of a vapor bubble in nucleate boiling respectively using thermochromic liquid crystals and observed a strong wall temperature drop close to the micro region. In the micro scale studies, the evaporating thin film profile were

* Corresponding author. Tel.: +91 80 25083211; fax: +91 080 25083203.
E-mail addresses: jasvanth@isac.gov.in (V.S. Jasvanth), ambi@isac.gov.in (A. Ambirajan), jaywant@mecheng.iisc.ernet.in (J.H. Arakeri).

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Nomenclature

$2w$	slot width (m)
$\Delta\hat{P}_c$	non-dimensional pressure ($\Delta P_c/\Delta P_{c,0}$)
ΔP_c	sum of disjoining pressure and capillary pressure (N m^{-2})
ΔP_l	liquid pressure drop (N m^{-2})
ΔP_v	vapor pressure drop (N m^{-2})
ΔT	temperature drop ($^\circ C$)
$\dot{m}$	evaporation mass flow rate (kg s^{-1})
$\hat{Q}_{mic}$	non-dimensional heat transfer $\hat{Q}_{mic}/k_l(T_w - T_{sat})$)
$\hat{\delta}'$	non-dimensional slope (δ/δ_0)
$\bar{M}$	molecular weight (kg mol^{-1})
$\bar{R}$	universal gas constant (J mol^{-1} K^{-1})
A	dispersion constant (J)
f	accomodation coefficient
h	wicking height (m)
h_{fg}	latent heat of evaporation (J kg^{-1})
K	interface curvature (m^{-1})
k_l	liquid conductivity (W m^{-1} K^{-1})
P_c	capillary pressure (N m^{-2})
P_d	disjoining pressure (N m^{-2})
P_l	liquid pressure (N m^{-2})
P_v	vapor pressure (N m^{-2})
$P_{lv\text{-}eq}$	equilibrium pressure of liquid vapor interface (N m^{-2})
P_{sat}	saturation pressure (N m^{-2})
$P_{v\text{-}eq}$	equilibrium vapor pressure (N m^{-2})
Q	heat flow (W m^{-1})
q''_{evap}	interface net heat flux (W m^{-2})
$Q_{mic,w}$	cumulative heat transfer (W)
Q_{mic}	cumulative heat transfer per unit depth (W m^{-1})
R_c	meniscus radius of curvature (m)
R_g	specific gas constant (J kg^{-1} K^{-1})
T	Temperature ($^\circ C$)
u	velocity in x-direction, (ms^{-1})
V	molar volume (m^3 mol^{-1})
W	depth of capillary slot (m)
X	non-dimensional length (x/δ_0)
x	abscissa (m)
x_{men}	meniscus height (m)
y	ordinate (m)

Greek symbols

δ	liquid film thickness (m)
δ_0	non-evaporating film thickness (m)
μ_l	liquid viscosity (N s m^{-2})
μ_v	vapor viscosity (N s m^{-2})
ν_l	kinematic viscosity (m^2 s^{-1})
ρ_l	liquid density (kg m^{-1})
ρ_v	vapor density (kg m^{-3})
σ	surface tension (N m^{-1})
θ	apparent contact angle (deg)
ε_1	initial value of non-dimensional slope, $\hat{\delta}'$
ε_2	initial value of $\hat{Q}^{mic}$

Subscripts

0	initial condition for adsorbed film
cap	capillary
l	liquid
lv	liquid–vapor interface
mic	micro or meniscus
sat	saturation condition
v	vapor
w	wall

developed using concepts such as: (1) the augmented Laplace–Young relation which accounts for both the effects of intermolecular forces (disjoining pressure) and capillary forces, (2) the simplified evaporation mass flux model across a liquid–vapor interface originally derived by Schrage [14] based on classical kinetic theory, (3) the combined Kelvin and Clausius–Clapeyron relationships, (4) heat conduction across the meniscus and (5) the lubrication theory of fluid flow; and were are correlated with the experimental observations. The above microscale studies showed that there is intense evaporation in the submicron region of the evaporating liquid–vapor interface leading to an apparent contact angle and this contact angle increases with superheat [11].

At the pore scale: (i) a constrained vapor bubble with a liquid–vapor meniscus in a heated capillary tube simulating the conditions of a PHP and (ii) the evaporating meniscus with capillary flow in small diameter capillary tubes, slots and V-grooves have been investigated. Rao et al. [15,16] experimentally analyzed a liquid plug with a vapor bubble in a capillary tube to explain the self-sustained thermally-induced oscillations of a PHP and highlighted the importance of the evaporating thin-film in the PHP model. Srinivasan et al. [17] experimentally analyzed the evaporation of a liquid methanol plug moving through a capillary tube using a high speed camera. Niclos et al. [18] experimentally studied the evaporation of a liquid film deposited downstream a semi infinite slug flow in a heated copper capillary tube and measured the wall temperatures using infrared (IR) thermography. Nikolayev [19] analyzed the oscillatory instability of a gas liquid meniscus in a capillary tube under an imposed temperature difference to determine the start-up thresholds in a PHP. These studies highlighted the importance of evaporating thin-film during the motion of liquid plug in a PHP.

Stefan and Busse [20] developed a model utilizing the thin-film theory at the micro scale for an evaporating meniscus in the grooves of a heat pipe and determined an apparent contact angle at a specific location in the meniscus. Khrustalev and Faghri [21] investigated a model of a capillary slot with liquid and vapor phases separated by a evaporating meniscus with an assumed apparent contact angle and a constant radius of curvature. Morris [22] hypothesized that an evaporating meniscus of a perfectly wetting fluid exhibits an apparent contact angle that is a function of the superheat and fluid properties.

Pratt and Hallinan [23] presented an experimental investigation to study the dynamics of pentane evaporating meniscus in a heated capillary tube. From the wicking height measurements, they speculated that the increase in the contact angle is due to thermocapillary stress. The amount of heat that goes for evaporation was deduced from measured temperatures near the meniscus region with thermocouples mounted in holes drilled in the capillary tube. Pratt and Kihm [24] made similar observations from a single pore heated capillary experiment with a binary fluid mixture and wicking height measurements. Pratt et al. [10] experimentally studied the instability of a pentane meniscus in a capillary tube and speculated that thermo-capillary stresses emanating near the contact line plays an important role for the onset of instabilities. Ma et al. [25] analyzed an evaporating meniscus in a triangular groove and found that the contact angle increases with superheat. Ma et al. [26] developed a model for predicting the wicking height in a heated capillary tube using the evaporating thin-film theory,