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Experimental study of the heated contact line region for a pure fluid and binary fluid mixture in microgravity

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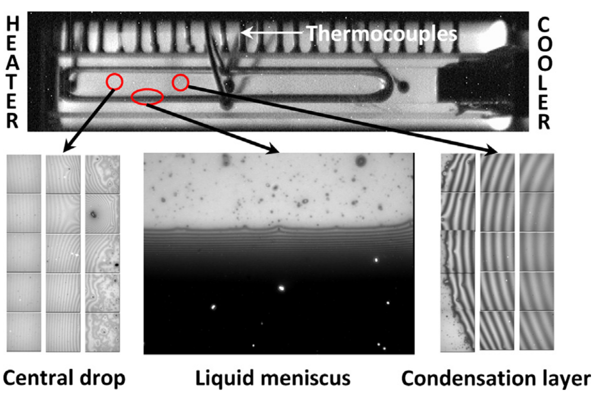
GRAPHICAL ABSTRACT



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ABSTRACT

Understanding the dynamics of phase change heat and mass transfer in the three-phase contact line region is a critical step toward improving the efficiency of phase change processes. Phase change becomes especially complicated when a fluid mixture is used. In this paper, a wickless heat pipe was operated on the International Space Station (ISS) to study the contact line dynamics of a pentane/isohexane mixture. Different interfacial regions were identified, compared, and studied. Using high resolution (50×), interference images, we calculated the curvature gradient of the liquid-vapor interface at the contact line region along the edges of the heat pipe. We found that the curvature gradient in the evaporation region increases with increasing heat flux magnitude and decreasing pentane concentration. The curvature gradient for the mixture case is larger than for the pure pentane case. The difference between the two cases increases as pentane concentration decreases. Our data showed that the curvature gradient profile within the evaporation section is separated into two regions with the boundary between the two corresponding to the location of a thick, liquid, "central drop" region at the point of maximum internal local heat flux. We found that the curvature gradients at the central drop and on the flat surfaces where condensation begins are one order of magnitude smaller than the gradients in the corner meniscus indicating the driving forces for fluid flow are much larger in the corners.

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Nomenclature

Roman symbols

A_c cross sectional area of the walls of the cuvette (m^2)
G, G_{min}, G_{max} gray value, minimum and maximum gray values
G_{bare} gray value of the bare quartz
$\bar{G}$ normalized gray value
h_{in} effective internal heat transfer coefficient (W/m^2 K)
k thermal conductivity of the cuvette material (W/m K)
K_y interface curvature in the Y-direction (1/m)
$K_{y,max}$ maximum curvature in the liquid meniscus (Y-direction) (1/m)
$K_{y,bulk}$ average curvature in the bulk region (Y-direction) (1/m)
ΔK_y curvature difference (Y-direction) (1/m)
n_l refractive index of the liquid mixture
n_1, n_2 refractive index of pentane and isohexane
n_s refractive index of the solid surface
n_v refractive index of vapor
P pressure at each experimental setting (Pa)
P_l liquid pressure along the liquid meniscus (Y-direction) (Pa)
P_v vapor pressure (Pa)
P_{in} and P_{out} inside and outside perimeters of the cuvette (m)
Q_{cond} conduction heat transfer rate (W)
$Q_{out,rad}$ thermal radiation heat transfer rate (W)
Q_{in} internal heat transfer rate (W)
q'_{cond} conduction heat flow per unit length (W/m)
$q'_{out,rad}$ outside radiation heat flow per unit length (W/m)
q'_{in} internal heat transfer flow per unit length (W/m)
RL, RL_{min}, RL_{max} reflectivity, minimum and maximum reflectivity
T temperature (K)
T_v temperature of the vapor (K)
T_2^{sat} saturation temperature of isohexane (K)
T_∞ temperature of the external environment (K)
x distance in the X-direction (m)
y distance in the Y-direction (m)
x_p mole fraction of pentane

Greek symbols

δ film thickness (m)
ε emissivity of the cuvette material
λ light wavelength (m)
Π disjoining pressure (Pa)
σ Stefan–Boltzmann constant ($W/m^2 K^4$)
σ_l surface tension of the liquid mixture (N/m)

1. Introduction

A wide variety of industrial processes and systems rely on phase change heat and mass transfer in the three-phase contact line region, the junction of the liquid with the vapor and the solid substrate (Fig. 1). The phase change heat transfer process in the liquid meniscus depends on two resistances: conduction and interfacial. Conduction resistance through a liquid film is proportional to the film thickness. Interfacial resistance happens at the liquid-vapor interface, is a function of the liquid film curvature, and is inversely proportional to the cube of the film thickness [1–4]. Based on the magnitude of these two resistances, the liquid meniscus can be segmented into three regions as shown in Fig. 1. In the thick meniscus region (bulk region), the conduction resistance is large and the interfacial resistance is small. In the adsorbed film region, the conduction resistance is small and the interfacial resistance is large. The total thermal resistance is minimized in the transition region or the contact line region, where the film thickness is small enough to make the conduction resistance small and large enough to make the interfacial resistance small. Therefore, the contact line region controls the transport processes in the thin liquid film.

Studies on the contact line region can be dated back to 1965 when Derjaguin et al. developed an evaporation theory based on disjoining pressure isotherms [5]. They demonstrated, for the first time, the connection between phase change heat transfer and basic interfacial forces. Later on, this idea was used by Potash and Wayner (1972) and Wayner et al. (1976) to describe the evaporation process from an extended liquid meniscus [6,7]. Broekhoff and de Boer (1968), Wayner (1982), Brochard-Wyart et al. (1991), and Sharma (1993) developed the film thickness profile at the contact line region using one-dimensional continuum models [8–11]. In 1992, Yang et al. used molecular dynamics to simulate the contact line region [12]. In the last several decades, a significant amount of work has been dedicated to understanding heat transfer and interfacial phenomena in the contact line region [13–23].

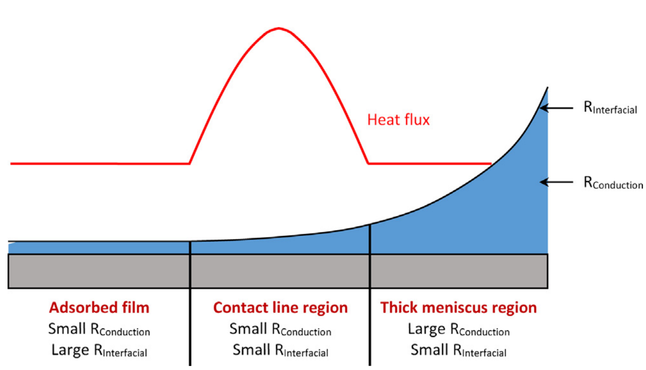

Fig. 1. Diagram of a liquid meniscus.

The phase change heat and mass transfer process in the three-phase contact line region, as well as the behavior of the contact line have been shown to be essential to understanding and controlling many processes including heat pipe operation, evaporation, condensation, nucleate boiling, coating, self-assembly processes, and a number of processes in biological systems. Studies by Faghri, Morris, Tso and Mahulikar, Peterson and Ma, Buffone et al. showed that the operating characteristics of heat pipes, especially wickless micro-heat pipes, depend on the dynamics of the contact line region [24–28]. This region also controls the spreading and wetting on non-heated [29,30] and heated surfaces [15,31], which in turn are critical phenomena in processes such as coating [32], self-assembly [33–35], boiling [30,31,36–39], and condensation [40]. The contact line region behavior also plays an important role in how bubbles nucleate, grow, and detach from a heated surface during boiling [41–44]. Beside the traditionally studied fields mentioned above, researchers have seen the effect of the contact line region in many biological systems as well. A few examples are the movement and spreading of mammalian cells [45], the adhesion of insect feet on solid surfaces [46], and the dynamics of tear films [47].

There is still much to understand about controlling contact line dynamics, especially at the micro- and nano-scale levels and when using multi-component mixtures. The Constrained Vapor Bubble (CVB) flight experiment is a miniature heat pipe operated on the International Space Station (ISS) to investigate contact line dynamics in microgravity. The heat pipe can be observed without fear of