Spreading Characteristics and Microscale Evaporative Heat Transfer In a Moving Meniscus Containing a Binary Mixture

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Prepared for presentation at AIChE 2005 Annual Meeting, Cincinnati, OH.

Extended Abstract

The interfacial phenomena in the contact line region of a curved liquid-vapor interface in contact with a solid surface are important to many equilibrium and non-equilibrium processes. The liquid phase in these processes can be pure liquids or mixtures. The transport processes and microscale evaporative heat transfer between a mixture and a solid surface are different compared to a pure liquid in contact with a solid surface. This difference, which can be constructive or destructive, is insufficiently explained in the literature due to the limitations in the resolution of the optical technique used. The present work is directed at alleviating this deficiency by taking the data for a mixture at the microscopic level with high spatial resolution. An improved data analysis procedure was used to compare the measured film thickness profiles during spreading and evaporation of a pure liquid (pentane) and a binary mixture (pentane and octane) on a quartz surface for thicknesses, $\delta < 3$ μm.

Image analyzing interferometry was used to study the spreading characteristics of a liquid-vapor interface containing a binary mixture (initial concentration of 98 % pentane and 2 % octane by vol.) on a quartz surface. The thickness and curvature profiles in the contact line region of the meniscus were obtained using an improved data analysis procedure. The results obtained for the mixture were compared with those obtained for pure pentane under similar operating conditions. Isothermal experimental conditions of the meniscus were used for the in-situ estimation of the retarded dispersion constant. The experimental results for the pure fluid demonstrate that the disjoining pressure or the intermolecular interactions in the thin film region control the fluid flow within an evaporating completely wetting meniscus. Also, an imbalance between the disjoining pressure in the thin film region and the capillary pressure in the thicker meniscus region caused the evaporating pentane meniscus to spread over the solid (quartz) surface. Details of the procedure concerning the use with a pure system are presented in Ref. [Panchamgam et al., 2005a, 2005b].

For the mixture, the Marangoni flow (due to concentration driven stresses at the liquid-vapor interface) dominates over the disjoining pressure (in the thin film region) in

determining the spreading characteristics of the binary mixture meniscus. Here, the meniscus spreads over the quartz surface due to Marangoni flow towards the thin film region. With an upstream bulk mixture of 2 % octane and 98 % pentane, a shear stress due to the gradient of the liquid-vapor interfacial surface tension resulting from distillation controlled fluid flow in the contact line region. Also, a control volume model was developed to evaluate the differences between the pure fluid and the mixture.

Control Volume Model

The following force balance for the control volume of an oscillating pentane-octane film that includes the Marangoni stresses is an extension of previous work for a pure fluid [Panchamgam et al., 2005a]. Figure 1 illustrates the macroscopic interfacial force balance that relates viscous losses to interfacial forces and the local apparent contact angle in an evaporating meniscus for the control volume between δ_0 and δ_r. Due to the extremely small momentum of the system, we can assume that the sum of the forces acting on the interfaces of the control volume is balanced. Using a uniform vertical thickness for the control volume equal to δ_r, the cause of the liquid-vapor interfacial stress is included in the difference in the surface tensions at the ends of the control volume. Using the augmented Young-Laplace equation for the interfacial pressure jump, the horizontal component of the interfacial force balance between δ_r (measured at $\delta_r = 0.1\mu$m), and the flat liquid film on the quartz surface (at δ_0) is

$$\sigma_{lv,r}\cos\theta_r + \sigma_{ls,r} + (\sigma_{lv,r}K_r + \Pi_r)\delta_r = \tau_0 L_0 + \sigma_{lv,0} + \sigma_{ls,0} + (\sigma_{lv,0}K_0 + \Pi_0)\delta_0 \qquad (1)$$

where τ_0 is the average shear stress that the solid exerts on the fluid over the length L_0. The product $\tau_0 L_0$ represents a shear force per unit contact line length perpendicular to L_0 and is assumed to be positive towards the adsorbed thin film. Π_0 is the disjoining pressure at δ_r

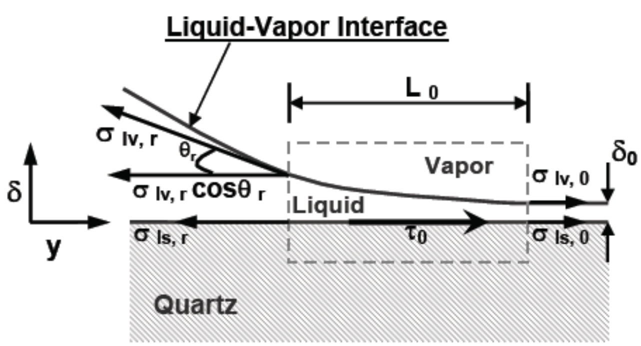

Figure 1. A schematic of the control volume of an evaporating corner meniscus for macroscopic interfacial force balance.

and θ_r is the value of the apparent contact angle at 0.1 μm. The sum ($\Pi_0\delta_0 + \sigma_{lv,0}\ K_0\ \delta_0$) represents the "suction" at δ_0 due to interfacial forces. The disjoining pressure or free energy per unit volume, Π_0, represents the force per unit area at the contact line and is positive for a completely wetting fluid. The value of the apparent contact angle is a function of the location because of the curvature, K. To overcome the difficulty of measuring the disjoining pressure at the thicker end of the control volume, the film thickness, δ_r, is taken to be the thickness at the first destructive interference fringe, 0.1 μm, where the disjoining pressure, Π_r, is negligible. Since, $\sigma_{lv,0} = \sigma_{lv,r} + \Delta\sigma_{lv}$; $\sigma_{ls,0} = \sigma_{ls,r} + \Delta\sigma_{ls}$, Marangoni shear is important with a mixture [Panchamgam et al., 2005c].

The conclusions from the complete paper [Panchamgam et al., 2005c]

- Using image analyzing interferometry, the thickness profile, in the range of δ_0 (adsorbed thickness) $< \delta < 3$ μm, at the leading edge of a moving ultra-thin film with phase change, was measured for a mixture of pentane-octane and compared with that of pure pentane.

- There were significant differences between the two systems demonstrating the presence of Marangoni shear stresses at the liquid-vapor interface.

- A control volume model was developed to evaluate the differences between the pure fluid and the mixture.

- The disjoining pressure at the leading edge controlled the evaporating pure system whereas its effect on the mixture was small for the fluxes studied.

- It appeared that the shear stress due to the gradient of the liquid-vapor interfacial surface tension resulting from distillation controlled fluid flow in the contact line region with an upstream bulk mixture of 2 % octane and 98 % pentane.

Acknowledgments

This material is based on the work supported by the National Aeronautics and Space Administration under grant number NNC05GA27G. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of NASA.

References

Panchamgam, S. S., Gokhale, S. J., DasGupta, S., Plawsky, J. L., and Wayner, P. C., Jr., "Experimental Determination of the Effect of Disjoining Pressure on Shear in the Contact Line Region of a Moving Evaporating Thin Film," *J. Heat Transfer*, 2005a; 127(3), 231-243.

Panchamgam, S. S., Plawsky, J. L., and Wayner, P. C., Jr., “Microscale Heat Transfer in an Evaporating Moving Extended Meniscus,” *Proceedings of ECI International Conference on Heat Transfer and Fluid Flow in Microscale*, Castelvecchio Pascoli, September 25-30, Italy, 2005b; (under review).

Panchamgam, S. S., Plawsky, J. L., and Wayner P.C. Jr., “Spreading Characteristics and Microscale Evaporative Heat Transfer in an Ultra-Thin Film Containing a Binary Mixture,” *J. Heat Transfer*, 2005c; (under review).