THE CONSTRAINED VAPOR BUBBLE HEAT PIPE
- ON EARTH AND IN SPACE

by

An Abstract of a Thesis Submitted to the Graduate

Arya Chatterjee

A Thesis Submitted to the Graduate

Faculty of Rensselaer Polytechnic Institute

in Partial Fulfillment of the

Requirements for the degree of

DOCTOR OF PHILOSOPHY

Major Subject: Chemical Engineering

The original of the complete thesis is on file
in the Rensselaer Polytechnic Institute Library

Approved by the
Examining Committee:

Peter C Wayner Jr., Thesis Adviser

Joel L. Plawsky, Thesis Adviser

Yoav Peles, Member

Shekhar Garde, Member

Patrick T. Underhill, Member

Rensselaer Polytechnic Institute
Troy, New York

December, 2010

ABSTRACT

Heat pipes are in most laptops; they are on the Hubble Space Telescope and on the Mars rovers. They are the top contenders for the next generation of cooling devices that will become necessary for the microprocessors of the future. Heat pipes work on the principle of phase change, i.e., they utilize the latent heat of the working fluid to transport the heat. To transport mass, heat pipes use surface tension, which makes these devices simpler and more reliable than systems where the working fluid needs to be actively pumped. They are especially useful in space, where, in the absence of gravity, surface tension becomes dominant. The operation of a heat pipe is extremely complex because the two widely different length scales involved. The first scale, that is of the order of the device length, concerns the capillary pumping of the working fluid along the axis of heat transfer, while the second, which involves the evaporation at the three phase contact line region, is of the order of a hundred nanometers. The Constrained Vapor Bubble experiment obtained data to probe the complex interfacial transport at both these scales.

The Constrained Vapor Bubble is a transparent, wickless heat pipe. Being constructed from a spectrophotometer cuvette, it allows optical inspection of the multiple scales (involved in the operation of a heat pipe) via microscope. The image data from the experiment can be used to determine the spatial ditails of the curvature of the liquid-vapor interface. At lower magnification, one can determine the axial curvature gradient (and, hence, the pressure gradient) to a very high resolution that is unique in the literature. The pressure gradient can be used to determine the fluid flow. The amount of fluid evaporated can be calculated from the change in flow; wherefrom, the evaporative heat transfer can be determined. The instrumentation leads to unprecedented accuracy in temperature and pressure determination.

Three heat pipes of various lengths were built by NASA in collaboration with RPI. They were operated on earth and then flown to the International Space Station and run in space. Very interesting phenomena occur in the absence of gravity. While

the performance of the CVB heat pipe is enhanced due to increased fluid flow, loss of convection, as a heat loss mechanism in the space environment, leads to a difference in the details of transport processes.

As on Earth, most of the evaporation occurs at the contact line of the CVB heat pipe and it is the focus of the second part of the thesis. Experimental data was also collected from a loop heat pipe that is very similar to the CVB in construction. It was observed that the contact line oscillates at high heat fluxes and these oscillations depend on the local heat flux. Using higher magnification and an interferometry technique the shape of the liquid-vapor interface (thickness, slope-angle and curvature) at the contact line was determined, which again provided the curvature (and thence the pressure) gradient, albeit at the microscopic scale. Data analysis revealed distinct correlation between the oscillations and the adsorbed film thickness, curvature and slope-angle of the meniscus. The disjoining pressure at the adsorbed film together with capillary pressure due to the curvature of the liquid vapor interface formed the boundary conditions at the two ends of the oscillating film. A theoretical analysis of the meniscus showed that the system is inherently unstable due to the imbalance between the liquid draining effect of Marangoni stress and liquid resupply by the adhesion and capillary forces.

The CVB experiment on the ISS has provided new insights into the working of a grooved heat pipe in microgravity and generated valuable data that change our understanding of how they behave in the absence of gravity. The models developed will aid in designing next generation heat pipes. The oscillations at the contact line show that the evaporating meniscus, the heart of any heat pipe, is a complicated, phenomena-rich region.