Abstract

Thermal management of electronic chips has become a bottleneck in the advancement of semiconductor technology due to continuously shrinking size, increasing transistor density and integration of multiple functions on a single chip. This problem has been further aggravated by the small form factor of the electronic devices. Due to these factors, conventional cooling methods such as conduction and convection are no longer adequate for heat load management of micro-electronics. For the development and advancement of the next generation of electronic devices, it is essential to develop effective, efficient and preferably passive thermal management solution. Miniature heat pipes (MHPs) offer an efficient means of passively removing heat from microelectronic equipment using phase change phenomenon. MHPs in their current state can only transfer heat of order $10 \text{ W cm}^{-2}$. Therefore, any further improvement in the maximum heat transfer capacity of MHPs will help in dealing with growing challenges of thermal management of micro-electronics. There are a variety of methods to enhance the heat transfer performance of an MHP such as geometry, working fluid, and the wettability of its inner surface. Recently, treating the inner surface of the MHP for wettability gradient has been shown to enhance its thermal performance. This dissertation deals with the mathematical modelling of heat pipes with wettability gradient.

We begin by presenting a quasi one-dimensional mathematical model to analyse the effect of wettability gradients on the steady-state thermal performance of conventional MHP. Our model takes into account the effect of axially varying contact angle and corresponding variation in friction factor. We use lubrication approximation to model the liquid flow through micro-grooves of the MHP. For our analysis, we consider MHPs with various wettability schemes, such as uniform, step-variation, and linear variation in the contact angle. Our model predictions show that increasing the wettability of the evaporator surface and reducing the wettability of the condenser surface of MHP can lead to an increase in the heat transfer capacity of MHP by over 35%. We demonstrate the
favourable effect of wettability gradients on MHP performance for different working li-
quids over a wide range of operating temperature and liquid charge. We also discuss the
underlying physical mechanism that leads to the enhanced thermal performance of MHP
with mixed wetting surfaces. We show that the optimal choice of wettability gradient
in MHP is governed by the competing effects of high liquid flow resistance in the lower
wetting condenser and high liquid mass in the higher wetting evaporator.

Next, we use our mathematical model to optimize the wettability gradient under the
constraints of the maximum and minimum value of the contact angle to obtain the best
possible thermal performance of an MHP. We perform the calculation for MHPs filled
with (i) a given mass of working fluid and (ii) ideal mass of working fluid. The MHP with
optimal wettability gradient has uniformly high wetting evaporator and uniformly low
wetting condenser. The primary gradient in wettability lies in the adiabatic section. Our
calculations show that compared to MHP with uniform high wettability using optimal
wettability gradient leads to more than 90% increase in maximum heat transfer capacity
of the MHP. We also show that the optimal wettability gradient is almost independent
of the fluid charge.

Relatively small wettability gradient in conventional MHP enhances capillarity, but
does not change the basic operating principle of MHP. However, large wettability gradient
leads to spontaneous motion of condensed drops and change in condensation mechanism
from filmwise condensation (FWC) to dropwise condensation (DWC). Based on these
effects a diode heat pipe can be developed wherein condensed drops move spontaneously
from condenser (low wetting region) to evaporator (high wetting region). We present
physical limits of heat transfer of a diode heat pipe whose operation is based on the
spontaneous motion of condensed drops on a surface with wettability gradient. The heat
transfer capacity of a diode heat pipe is limited by (i) dropwise condensation (DWC) heat
transfer, (ii) capillary limit of the wick and (iii) entrainment of condensed drops by vapour.
We calculate the capillary limit of the heat pipe using Darcy’s law for flow through a porous media. To model entrainment limit, we use the creeping flow approximation for drag on a hemispherical droplet due to counter-flowing vapour. For DWC, we present a mathematical model based on population balance to model DWC on a surface with wettability gradient. In this model heat transfer through a single drop of given radius is combined with respective drop population and then integrated over drop size distribution to calculate the heat transfer through the surface. Our model takes into account the effect of wettability gradient and energy released during drop coalescence model to determine the drop departure size. We validate our model with published experimental data of DWC heat flux and drop size distribution. We also propose a mechanism that explains how the energy released during drop coalescence on a surface with wettability gradient and in a condensation environment aids drop motion. The mechanism correctly explains the shift of center of mass of two coalescing drops on a surface with wettability gradient towards the drop on the high wetting region. Using the model, we analyze the effect of wettability gradient on the DWC heat flux. Our model predictions show that the optimal choice of wettability gradient is governed by differential variations in population density and heat transfer through a drop with change in wettability of the surface. We also demonstrate that contact angle at which there is maximum heat transfer through a drop varies with the thickness of coating layer leading to change in optimal wettability gradient. Using the mathematical model for DWC on a surface with wettability gradient, we calculate the limit of DWC heat transfer. We show that among the three limits maximum heat transfer capacity of the diode MHP is governed by DWC heat transfer.

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