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The coupled effects of working fluid and solid wall on thermal performance of micro heat pipes

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ABSTRACT

By incorporating the solid wall conduction, together with the continuity, momentum, and energy equations of the liquid and vapor phases, a mathematical model is developed based on the conservation laws and is solved to yield the heat and fluid flow characteristics of micro heat pipes. This work provides a comprehensive and insightful analysis on the effects of working fluid and solid wall on the thermal performance of micro heat pipes. The characteristics and performance of different types of working fluid and solid wall are elucidated. A well-defined exposition of the circulation effectiveness of the working fluid is proposed and the operation regime map for different types of working fluid is conceived for the identification of the optimal operating conditions. The coupled role of working fluid and solid wall is quantified by deriving a new non-dimensional group, which can be used to characterize the contribution of working fluid and the solid wall to the heat transport rate. The present study serves as a useful analytical tool in the micro heat pipe design and performance analysis, associated with the selection of both working fluid and solid wall material for specific operating conditions.

1. Introduction

The miniaturization development of electronic components such as high-performance microprocessors leads to significant increase in problems associated with the overheating of the components [1]. It has been pointed out that the mean time to failure of a microelectronic component can as much as be doubled with only a 10 °C decrease in its operating temperature [2]. Following this, the demanding heat removal poses formidable challenges to the thermal management community to exploit efficient methodology for heat dissipation due to the fact that both reliability and lifespan of the electronic components are inversely related to the operating temperature limit [3,4]. Since it was first proposed by Cotter [5] in 1984, micro heat pipe manifests itself as a promising cooling device. Even within a constrained space in the electronic devices, micro heat pipes can provide sufficient cooling effects on the microelectronic chips due to their relatively small dimensions, normally with a hydraulic diameter on the order of 100 μm and an average length of few centimeters. Unlike conventional heat pipe, a micro heat pipe does not contain a wick structure. It utilizes the capillary pressure induced by the sharp-angle corners to circulate the condensate back to the evaporator section [6]. In some of the cases to suit various applications, the analysis of micro heat pipe arrays have been compared with that of conventional heat pipes with micro-grooved wick structure [7–12]. The heat transport capacity of heat pipes with grooved wick structure increases with the decrease of the wick width since narrower wick produces higher pumping capability to circulate the condenser back to the evaporator section [13]. Fig. 1 shows a schematic diagram of a micro heat pipe of triangular cross-section. A fraction of the heat applied to the evaporator section is axially conducted towards the condenser section through the solid wall while the major portion of the heat input is absorbed as latent heat of evaporation by the liquid confined at the sharp corners by the action of surface tension [14]. The resultant vapor will then flow through the adiabatic section, where no heat transfer takes place between the micro heat pipe and its surroundings, towards the condenser section. The vapor condenses at the condenser section and the latent heat of evaporation is dissipated to the surroundings. The vaporization and condensation of the working fluid take place continuously resulting in heat dissipation through the condenser section, which accounts for both the heat conduction in the solid wall and the latent heat released by the condensing vapor. The capillary action results in a drop in the liquid pressure from the condenser to the evaporator, whereupon the resultant pressure drop drives the condensate back to the evaporator and the cycle of

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Nomenclature

A	cross-sectional area, m^2
Bo	Bond number, defined in Eq. (21)
C	dimensionless geometrical parameter
Ca	capillary number, defined in Eq. (22)
D_H	hydraulic diameter, m
f	friction factor
g	gravitational acceleration, m/s^2
h_{fg}	latent heat of evaporation, J/kg
L_t	total length of micro heat pipe, m
M	mass of working fluid, kg
M	charge level
M_{opt}	optimal charge level
$\dot{m}$	mass flow rate, kg/s
$\hat{m}$	dimensionless mass flow rate
$\dot{m}_{ref}$	reference mass flow rate, defined in Eq. (19), kg/s
N	number of corners
P	contact length, m
p	pressure, N/m^2
$\hat{p}$	dimensionless pressure
Po	Poiseuille number, defined in Eq. (14)
$\dot{Q}$	heat transport rate, W
$\dot{Q}_{cap}$	heat transport capacity, W
$\dot{q}$	rate of heat transfer per unit axial length, W/m
Re	Reynolds number, defined in Eq. (15)
r	meniscus radius of curvature, m
T_{op}	operating temperature, °C
u	velocity, m/s
We	Weber number, defined in Eq. (23)
w	groove width, m
x	axial distance from evaporator end, m
$\hat{x}$	dimensionless x

Greek symbols

β	angle of inclination, rad
γ	kinematic viscosity ratio, defined in Eq. (24)
ψ	density ratio, defined in Eq. (26)
ε	aspect ratio, defined in Eq. (25)
θ	contact angle, rad
μ	dynamic viscosity, kg/s m
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	surface tension, N/m
τ	shear stress, N/m^2
ϕ	half corner apex angle, rad
ξ	volume fraction occupied by liquid phase
Ω	angular parameter, defined in Eq. (51)

Subscripts

a	adiabatic section
c	condenser section
cl	capillary limit
e	evaporator section
fl	onset of flooding
l	liquid
lv	liquid–vapor interface
sl	solid–liquid interface
sv	solid–vapor interface
v	vapor

phase-change and circulation is perpetuated. A number of theoretical studies on thermal performance of micro heat pipes have been reported to understand the steady-state [6,15,16] and transient [9,17–19] characteristics, as well as to optimize the operating conditions of micro heat pipes in order to enhance the overall thermal performance [20–23].

Judging from the fact that the phase-change heat transfer of the working fluid and the heat conduction through the solid wall constitute the two major heat transport processes taking place in a micro heat pipe, the roles of the working fluid and the solid wall material on the overall thermal performance of a micro heat pipe are of paramount importance [14]. Like the conventional heat pipe, the selection of appropriate combination of working fluid and solid wall material is an important design and fabrication issue of a micro heat pipe [24]. In identifying a suitable working fluid for a designated range of operating temperature, the heat transport capacity of a micro heat pipe is the foremost consideration [2,5,6,14]. In addition, the issue of compatibility of working fluid with solid wall material and the results of life tests are cardinal aspects in the design and fabrication of a micro heat pipe. Most notably, the generation of noncondensable gases due to the incompatibility of the combination of working fluid and solid wall material adversely affects the thermal performance of heat pipes [24]. Among a wide range of working fluids, water is the most widely used working fluid in a micro heat pipe [2,6,14,22,25,26]. Other common working fluids include acetone [27], ammonia [28], ethanol [29,30], methanol [29,31], and pentane [18,20,32]. Thus far there are only two existing theoretical studies in the literature particularly characterizing the effect of variations in thermo-physical properties of working fluids on the thermal performance of micro heat pipe [20,33]. A theoretical study has been performed to examine the effect of variations in the thermo-physical properties, particularly, the surface tension and the viscosity of pentane, on the thermal performance of a V-shaped micro grooved heat pipe [20]. A deviation in the range of 10% of the surface tension and the viscosity was manipulated to evaluate the radius of curvature of the liquid meniscus in the axial direction of the micro grooved heat pipe. However, such manipulation of thermo-physical properties of a single working fluid neither practically provide a comprehensive picture nor useful information in the selection of suitable working fluid for a micro heat pipe. On the other hand, using a porous medium model, Sugumar and Tio [33] performed a more comprehensive study on the effect of working fluid on the thermal performance of a micro heat pipe by considering different types of common working fluid over a practical range of operating temperature; however, the solid wall effect was not included. They pointed out that the heat transport capacity of a micro heat pipe is dominated by the circulation rate, which is the ratio of the surface tension and dynamic viscosity of the working fluid. Using the heat transport capacity as a performance indicator, they suggested that ammonia is a promising candidate for operating temperatures below 50 °C while water should be chosen for temperatures above 50 °C.

As the working fluid is commonly known as the key player responsible for the heat transport of a micro heat pipe, most of the theoretical investigations in the literature mainly focused on the transport processes of the working fluid without taking into account the solid wall effects of the micro heat pipes. The solid wall temperature in the axial direction is either assumed to be uniform or its effects are not taken into account in the analysis. Therefore, up to date, there are only a limited number of theoretical investigations on the solid wall effects of micro heat pipe available in the existing literature. As reported by the studies considering thermal effect of the solid wall such as those by [14,15,20,26,34–36], it