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Dielectric liquid pumping flow in optimally operated micro heat pipes

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ABSTRACT

Micro heat pipe is a micro-scale capillary-driven two-phase heat transfer device of which thermal performance is governed by the strength of evaporation and the circulation effectiveness of condensate from the condenser to the evaporator. By employing a mathematical model based on the conservation laws, this study demonstrates the application of dielectric pumping flow in enhancing the circulation effectiveness of condensate and hence the thermal performance of micro heat pipes. Through the application of a non-uniform electric field, the Maxwell pressure gradient is induced to drive the condensate flowing towards the evaporator. Two different dielectric pump configurations are compared and the micro heat pipe using planar electrodes is found performing better than that with the pin electrodes. The performance enhancement of different dielectric pump lengths where the total amount of electrical energy of the pump is conserved is analysed. The dielectric pump performs the best when it covers the entire length of micro heat pipe. Compared to the case without dielectric liquid pumping flow, significant enhancement in the heat transport capacity can be obtained where the maximum enhancement exceeds 220%. Even with a significant performance enhancement, the use of dielectric pump renders a sufficiently small solid wall temperature drop of a micro heat pipe, justifying the typical characteristic of a phase-change heat transfer device.

1. Introduction

Towards the goal of improved thermal management in micro-electronics, micro heat pipe renders a promising approach due to the fact that it can provide sufficient cooling effect even within a constrained space in the electronic device. Since the idea of micro heat pipe was proposed by Cotter [1] in 1984, this micro-scaled cooling device has been studied actively, either theoretically or experimentally, following the dramatic development in the electronic and micro-electronic industries in the recent years. Micro heat pipe possesses various advantages over other electronics cooling devices due to its benefit mostly from the phase-change and circulation effectiveness of working fluid. As shown in Fig. 1, micro heat pipe is a wickless capillary microchannel of which capillary pressure is induced by the sharp-angle corners. The heat loaded to the evaporator section is mainly absorbed as latent heat of evaporation by the liquid confined at the sharp corners. The remaining small fraction of the heat is conducted axially in the solid wall towards the condenser section [2,3]. The resultant vapour flows towards the condenser section through the adiabatic section, and condenses at the condenser section where the latent heat of evaporation is dissipated to the surroundings. The capillary action induced at the sharp-angle corners due to the resultant liquid pressure drop from the condenser to the evaporator drives the condensate back to the evaporator to perpetuate the cycle of phase change and circulation of the working fluid. The maximum possible heat transport rate, denoted as the heat transport capacity, is obtained when the simultaneous onsets of dryout at the evaporator end and flooding at the condenser end take place [2,3]. When the micro heat pipe is overloaded (the heat input exceeds the heat transport capacity), dryout transpires at the evaporator section and the sharp-angled corners are depleted of liquid due to the fact that the capillary pressure is incapable of supplying an adequate amount of working fluid rapidly enough to the evaporator section to compensate for the liquid loss through the immense evaporation rate. The excessive condensate, which is not circulated to the evaporator section, accumulates in the condenser end and flooding occurs. A liquid block is formed, hindering the condensation heat transfer and thus reducing the effective condenser length of the micro heat pipe.

The transport phenomena taking place in micro heat pipes are considerably complicated, encompassing the principles of fluid mechanics and phase-change heat transfer. The thermal performance of a micro heat pipe is essentially governed by its circulation effectiveness of working fluid [3]. External force induced by

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Nomenclature

A	cross-sectional area, m^2
$\mathrm{Bo_P}$	ponderomotive Bond number, defined in Eq. (26)
Bo	Bond number, defined in Eq. (24)
C	dimensionless geometrical parameter
Ca	capillary number, defined in Eq. (25)
D_H	hydraulic diameter, m
d	distance between the tip of pin and planar electrodes, m
$\mathbf{E}$	electric-field vector, V/m
$\hat{F}_e$	dimensionless electric body force term, defined in Eq. (23)
f	friction factor
$\mathbf{f}$	electric body force density, N/m^3
g	gravitational acceleration, m/s^2
h_{fg}	latent heat of evaporation, J/kg
K	integration constant
k	thermal conductivity, W/m · K
L_t	total length of micro heat pipe, m
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, kg/s
$\bar{\dot{m}}$	average mass flow rate, defined in Eq. (38), kg/s
N	number of corners
Nu	Nusselt number, defined in Eq. (40)
P	contact length, m
p	pressure, N/m^2
$\hat{p}$	dimensionless pressure
Po	Poiseuille number, defined in Eq. (15)
$\dot{Q}$	heat transport rate, W
$\dot{Q}_{cap}$	heat transport capacity, W
$\dot{q}_w$	heat transfer rate per unit axial length, W/m
Re	Reynolds number, defined in Eq. (16)
r	meniscus radius of curvature, m
T	temperature, °C
T_{op}	operating temperature of micro heat pipe, °C
t_w	wall thickness, m
u	velocity, m/s
V	applied voltage, V
We	Weber number, defined in Eq. (27)
w	groove width, m
x	axial distance from evaporator end, m
$\hat{x}$	dimensionless x

Greek symbols

α	aspect ratio, defined in Eq. (30)
β	angle of inclination, rad
ε	dielectric permittivity, C/V · m
Φ	volume fraction occupied by liquid phase
ϕ	half corner apex angle, rad
Γ	circulation parameter, defined in Eq. (37), kg/m · s
γ	kinematic viscosity ratio, defined in Eq. (29)
μ	dynamic viscosity, kg/s · m
ν	kinematic viscosity, m^2/s
ϖ	density ratio, defined in Eq. (28)
θ	contact angle, rad
ρ	density, kg/m^3
ρ_e	volume charge density, C/m^3
σ	surface tension, N/m
τ	shear stress, N/m^2
Υ	angular parameter, defined in Eq. (61)

Subscripts

a	adiabatic section
c	condenser section
cl	capillary limit
dp	dielectric liquid pump
e	evaporator section
fl	onset of flooding
j	phase j
l	liquid
lv	liquid-vapour interface
m	maximum
s	solid wall
sl	solid-liquid interface
sv	solid-vapour interface
v	vapour
x	x-direction
y	y-direction
z	z-direction
0	evaporator end
1	condenser end

electric field is widely applied to generate fluid motion in a favourable direction for enhancing the circulation effectiveness. The incorporation of electrohydrodynamically-driven flow is a promising approach in enhancing the performance of a microfluidic device [4]. Electrohydrodynamic (EHD) or electrokinetic flows are induced by the application of an electric field to incorporate a net electrostatic (Maxwell) force in polarized surface regions in order to drive the fluid flow or to induce the motion of particles suspended within the liquid [4,5]. In practical applications, either a DC or an AC high-voltage low-current electric field is applied through a pair of charged and receiving electrodes [5]. Generally, attributed to the applied electric field, the electric body force density, $\mathbf{f}$, which is more commonly known as Korteweg-Helmholtz force density, is given by [4]

$$\mathbf{f} = \rho_e \mathbf{E} - \frac{1}{2}\nabla\left(\varepsilon - \rho \frac{\partial \varepsilon}{\partial \rho}\bigg|_T\right)\mathbf{E}\cdot\mathbf{E}, \tag{1}$$

where ρ_e is the volume charge density and $\mathbf{E}$ being the electric-field vector. The first term on the right-hand side of Eq. (1) represents the Coulombic force, which arises due to the presence of the free space charges while the second term consists of the ponderomotive force term and the electrostrictive term. The ponderomotive force term arises due to the inhomogeneity of the dielectric permittivity, ε, which describes the permittivity change occurs at the liquid-vapour interface. On the other hand, the electrostrictive term accounts for the compressibility of the media which is negligible for incompressible fluids [4]. In the absence of electrostrictive effects, two general principles of inducing electrohydrodynamic actuation are either through the generation of free space charges to engender Coulombic forces or through the polarization of induced charges by applying an electric field to trigger ponderomotive forces [4]. The Coulombic force acts on the free space charges within the fluid. A viable method of producing space charges in the fluid is by directly charging electrolyte solution to the working fluid such that electroosmotic flow can be induced because of the presence of free ions in the electrolyte solution [6,7]. A recent study by Chang and Hung [8] demonstrates the use of electroosmotic flow to increase the circulation rate of working fluids in micro heat pipes. Significant enhancement in thermal performance of micro heat pipe has been achieved.