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Electroosmotic flow in optimally operated micro heat pipes

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ABSTRACT

Micro heat pipe, a capillary-driven two-phase heat transfer microsystem, serves as an effective cooling device for electronic components. Based on a mathematical model employing the conservation laws to yield the heat and fluid flow characteristics of a micro heat pipe, we demonstrate how the basic principles of electroosmotic flow can be applied to enhance the performance of micro heat pipes. To provide a thorough and comprehensive analysis, both favorable and adverse effects of electroosmotic flow on the thermal performance of a micro heat pipe are studied. The thermal performance of a micro heat pipe is strongly dependent on the circulation effectiveness of working fluid. A well-defined parameter is employed to characterize the effects of the electric force on the circulation effectiveness of the working fluid with different ion concentrations. The aiding effect of electric force increases the circulation rate of working fluid, resulting in a significant enhancement in the heat transport capacity of micro heat pipe. By investigating the solid wall temperature profiles, the use of electroosmosis in enhancing the thermal performance of a micro heat pipe is deemed to be practically feasible due to the fact that significant enhancement can be achieved with a compensation of small temperature drop at a reasonably low applied voltage.

1. Introduction

In view of miniaturization of electronic components in the recent years, complications related with overheating of these components have been significantly increased [1,2]. In order to ensure a longer life-span and higher reliability of electronic components, it is essential to apply effective cooling methods to dissipate the undesired heat generated. Following this, micro heat pipe, a capillary-driven two-phase heat transfer system, is a prospect for effective micro-scale heat removal due to its relatively small dimensions and great capability in dissipating high heat flux [3,4]. In light of its small dimensions with an average length of a few centimeters and a hydraulic diameter of the order of 100 μm [5], micro heat pipe stands out to be a promising candidate when space is a constraint. Micro heat pipe is a wickless channel whereby the capillary pressure induced by the sharp-angle corners circulates the condensate from the condenser back to the evaporator. Fig. 1(a) illustrates a schematic diagram of a micro heat pipe with square cross section. A major portion of the heat loaded to the evaporator section is absorbed as latent heat of evaporation by liquid confined at the sharp corners. The remaining minor fraction of the heat is conducted axially in the solid wall towards the condenser section [6,7]. The resultant vapor flows towards the condenser section through the adiabatic section, and condenses at the condenser section. The latent heat of evaporation together with the heat conducted through the solid wall is dissipated to the surroundings. The capillary action induced by the resultant liquid pressure drop from the condenser to the evaporator drives the condensate back to the evaporator. Thus, the cycle of phase change and circulation of the working fluid is perpetuated.

The thermal performance of a micro heat pipe is strongly dependent on the effectiveness of circulation and strength of evaporation of working fluid [5–10]. External force induced by electric field can be used to generate fluid motion in a favorable direction for enhancing the circulation effectiveness. From micro-scale perspective, it has been pointed out that electrohydrodynamically-driven micro heat pipes provide an overall mass saving that is useful where constrained space is the major concern [11]. In the presence of electrolyte solution in the working fluid, electroosmotic micropump is utilized to induce electroosmotic flow (EOF) associated with direct conversion of electrical energy into kinetic energy of the fluid [12–14]. Typically, EOF is generated when the surface charge on channel wall interacts with the charged ions in the working fluid, resulting in the formation of electric double layer on the surface. When an external electric field is applied to the system, the double layer and the fluid are forced to move in the direction of the electric force. EOF has been employed in a wide range of

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Nomenclature

A	cross-sectional area, m^2
$\mathrm{Bo_e}$	Electric Bond number, defined in Eq. (38)
Bo	Bond number, defined in Eq. (36)
C	dimensionless geometrical parameter
C_∞	bulk ion concentration, mol/m^3
Ca	capillary number, defined in Eq. (37)
D_H	hydraulic diameter, m
$\vec{E}$	electric-field vector, V/m
F	Faraday constant, C/mol
f	friction factor
$\vec{f}$	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, defined in Eq. (34), kg/s
N	number of corners
Nu	Nusselt number, defined in Eq. (16)
l	contact length, m
p	pressure, N/m^2
$\hat{p}$	dimensionless pressure
Po	Poiseuille number, defined in Eq. (28)
$\dot{Q}$	heat transport rate, W
$\dot{Q}_{cap}$	heat transport capacity, W
$\dot{q}$	rate of heat transfer per unit axial length, W/m
R	molar gas constant, J/mol·K
Re	Reynolds number, defined in Eq. (29)
r	meniscus radius of curvature, m
T	temperature, °C
T_K	operating temperature of EOF, K
T_{op}	operating temperature of MHP, °C
t_w	wall thickness, m
u	velocity, m/s
V	applied voltage, V
We	Weber number, defined in Eq. (39)
w	groove width, m
x	axial distance from evaporator end, m
$\hat{x}$	dimensionless x
z'	ion valency

Greek symbols

α	aspect ratio, defined in Eq. (42)
β	angle of inclination, rad
ε	dielectric permittivity, C/V·m
ϕ	half corner apex angle, rad
Γ	circulation parameter, defined in Eq. (56), kg/m·s
γ	kinematic viscosity ratio, defined in Eq. (41)
λ_D	Debye screening length, m
μ	dynamic viscosity, kg/s·m
ν	kinematic viscosity, m^2/s
ϖ	density ratio, defined in Eq. (40)
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	normalized heat transport capacity, defined in Eq. (55)
Ω	angular parameter, defined in Eq. (66)
ξ	volume fraction occupied by liquid phase
ψ	electric potential, V
ψ'	average cross-sectional electric potential, V
ψ_e	effective electric potential, V
ζ	zeta potential, V

Subscripts

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

applications such as soil remediation [15], micro-scale fluid mixing [16–19] as well as micro-scale liquid flow transportation systems [20]. Compared to other passive techniques such as the use of different types of working fluids [7,9] and the modification of geometry of micro heat pipe [21,22] in enhancing the performance, electroosmotic pumping offers higher controllability by modulating the ion concentration and the externally applied voltage. Electroosmotic pumping stands out from other pressure-driven methods with advantages of ease of fabrication, compactness, valveless control of liquid and omission of moving parts [23]. Therefore, it promises a higher accuracy in the control of transportation and manipulation of liquid flow by an electric field. This makes EOF a more favorable approach in microfluidic transport systems. Although EOF intrinsically requires high voltage, the corresponding current is very low resulting in a small electrical power consumption and therefore this type of configuration is generally safe. Various limitations governing the performance of electroosmotic pumps include the magnitude of externally applied electric field [24–26], the surface charge of solid surface [17,24–28], the ion density of working fluid [29,30] and the cross-sectional shapes of flow passage [24,31].

Previous studies of EOF in micro-scale internal flows were essentially associated with single-phase flow in microchannels [17,20,24,29–34]. It has been proven that the flow velocity can be significantly increased by inducing EOF in the microchannels. While the single-phase EOF has generated considerable interest in the contemporary research particularly in the field of microfluidics, investigations on two-phase EOF in micro-scale devices are absent in the literature. Therefore, the objective of this study is to demonstrate how the basic principles of EOF can be applied to a micro-scale phase-change heat transfer device – micro heat pipe. The circulation of working fluid driven by EOF is scrutinized through the liquid volume fraction distribution inside the micro heat pipe. Both favorable and adverse effects of the applied electric force on the thermal performance of micro heat pipe are investigated. The thermal performance of a micro heat pipe correlates highly with the circulation effectiveness of working fluid. By incorporating electroosmotic pump that operates without moving parts