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Numerical study of the electrohydrodynamic effects on the two-phase flow within an axially grooved flat miniature heat pipe

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ABSTRACT

A model for the fluid flow and heat transfer in an electrohydrodynamic (EHD) miniature heat pipe is presented. Coulomb and dielectrophoretic forces have been considered in the model. The coupled non-linear governing equations are developed and solved numerically. The variations of the liquid and vapor velocities and pressures as well as the liquid and vapor distributions along the Flat Miniature Heat Pipe (FMHP) are obtained. The electric field affects the liquid and the vapor velocities. It is also demonstrated that the vapor pressure drop increases with the electric field intensity, however, the liquid pressure drop decreases as the electric field strength increases. Moreover, the higher is the electric field intensity; the lower is the capillary pumping required for the liquid flow. This results into a lower liquid–vapor radius of curvature at the condenser. Similarly, the electric field affects the liquid–vapor shear forces as well as the liquid-wall and vapor-wall viscous forces. The analysis of the electric forces shows that the dielectrophoretic forces which act on the liquid–vapor interface are predominant and their order of magnitude is much higher than the Coulomb forces. It is also demonstrated that the capillary limit increases with the electric field, and the electric field reduces the dry-out when the applied heat input is higher than the capillary limit.

1. Introduction

The capillary structures used in Flat Miniature Heat Pipes (FMHPs) generally consist of microchannels, screen meshes, sintered metal powder, and metallic wires. The FMHPs, which are manufactured using such passive techniques, have fixed capillary pumping structures and only the operation conditions affect their thermal performances. Currently, active techniques, which specifically include the application of electric or magnetic fields, are investigated in order to be implemented in FMHPs using standard capillary structures. Thus, it appears that the use of the electrohydrodynamic effect (EHD) that consists of the application of an intense electric field is one of the most promising methods to improve the thermal performance of a FMHP. The use of the EHD technique has some advantages among them we can distinguish: (i) the heat transfer enhancement, (ii) reliable repriming of the FMHP including a passive capillary structure and (iii) the control of the thermal performance by the applied voltage.

The EHD miniature heat pipe works properly if the capillary and the electrohydrodynamic pressures are able to overcome the various pressure losses. This can be expressed by

$$\Delta P_{EHD} + \Delta P_c \Delta P_v + \Delta P_l + \Delta P_g \qquad (1)$$

where ΔP_{EHD} and ΔP_c are the electrohydrodynamic and the capillary pressures, respectively. ΔP_l and $\Delta P_v$are the pressure losses in the liquid and vapor phases, respectively. ΔP_g is the hydrostatic pressure.

The implementation of the EHD technique in FMHPs requires a good knowledge of the electrical phenomena but also the basic mechanisms governing the EHD coupling liquid–vapor phase change. The application of the EHD technique in cylindrical heat pipes began with the work of Jones [1–3] and Jones and Perry [4]. Other studies followed [5–18]. Next, the researches focused on the Capillary Pumped Loops (CPLs) and the Loop Heat Pipes (LHPs) [19–22], and more recently on FMHPs [23–26].

Hallinan et al. [23] and Yu et al. [24,25] have tested a FMHP including the EHD technique. The FMHP consists of a glass plate connected to a glass grooved plate each having a thickness of 1 mm. The total length of the FMHP is 28 mm. Seven axial and rectangular grooves (1 mm wide, 0.6 mm deep and 1 mm spacing) are machined by ultrasound technique. The axial grooves are

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Nomenclature

A	area, m^2
d	microchannel side, electrode spacing, m
D_g	groove height, m
D_h	hydraulic diameter, m
e	liquid height between the electrodes, m
E	electric field strength, V/m
E_o	electric field between two electrodes, V/m
E_h	electric field strength for the horizontal electrode arrangement, V/m
E_v	electric field strength for the vertical electrode arrangement, V/m
f	friction coefficient
f_s	interfacial electric stress, N/m^2
f_v	electric force per unit of volume, N/m^3
F_c	Coulomb force per unit of length, N/m
F_{diel}	dielectrophoretic force per unit length, N/m
F_i	interfacial liquid–vapor shear force per unit length, N/m
F_{lw}	liquid–vapor shear force per unit length, N/m
F_{vw}	vapor-wall shear force per unit length, N/m
g	gravity acceleration, m/s^2
h	height, m
h′	height, m
L	FMHP length, m
L_a	length of the adiabatic zone, m
L_b	length of the blocked zone in the condenser section, m
L_{dr}	length of the dried zone in the evaporator section, m
L_c	condenser length, m
L_e	evaporator length, m
$\dot{m}$	mass flow rate, kg/s
M_o	introduced fill charge, kg
$\bar{n}$	vector normal to the liquid–vapor interface
N_g	groove number
p_i	perimeter of the liquid–vapor interface, m
p_l	coefficient defined in Eq. (33)
p_{lw}	perimeter of the liquid-wall interface, m
p_{vw}	perimeter of the vapor-wall interface, m
P	pressure, N/m^2
Po	Poiseuille number
q_s	surface density of the electrical charges, C/m^2
q_v	volume density of the electrical charges, C/m^3
Q	heat input power, W
Q_a	axial heat flux rate, W
r_1, r_2	principal curvature radii of an interface, m
r_c	curvature liquid–vapor interface radius, m
Re	Reynolds number
T	temperature, °C
$\bar{t}$	tangent vector to the liquid–vapor interface
v	velocity, m/s
V	voltage, V
W_g	groove width, m
z	coordinate, m

Greek symbols

α	contact angle, °
β	inclination of the FMHP, °
Δh	height difference, m
Δh_v	latent heat of vaporization, J/kg
ΔP_c	capillary pressure, N/m^2
ΔP_{EHD}	electrohydrodynamic pressure, N/m^2
ΔP_g	hydrostatic pressure, N/m^2
ΔP_l	liquid pressure drop, N/m^2
ΔP_v	vapor pressure drop, N/m^2
ε	Absolute dielectric permittivity, F/m
ε_o	absolute dielectric permittivity of vacuum, F/m
μ	dynamic viscosity, kg/m.s
θ	angle defined by Eq. (38), °
ρ	density, kg/m^3
σ	surface tension, N/m
τ	shear stress, N/m^2

Subscripts

1	medium 1
2	medium 2
a	adiabatic
b	blocked
c	condenser, Curvature
h	horizontal
i	interfacial
il	interfacial (liquid side)
iv	interfacial (vapor side)
l	liquid
lw	liquid-wall
max	maximum
min	minimum
n	normal
sat	saturation
t	tangential
v	vapor, vertical
vw	vapor-wall
w	wall

connected to each end of the FMHP by a transverse groove in order to ensure uniform distribution of vapor and liquid within the axial grooves. The electrode connected to the high voltage is sandwiched between the glass plate and the grooved plate while the electrode serving as a mass is attached to the external wall of the grooved plate. Three pairs of aluminum electrodes are placed in the evaporation zone and the inter-electrode distance is 1 mm.

The electrode configuration adopted by Yu et al. [24] has several advantages. Indeed, the application of an electric field to the evaporator leads to a liquid pumping from the condenser to the evaporator because the liquid, whose permittivity is higher than that of vapor, tends to accumulate in the regions where the electric field is very intense. The liquid pumping is carried along the grooves having electrodes in the evaporation zone. The grooves which do not contain electrodes allow the vapor flow from the evaporator to the condenser.

The experimental results obtained by Yu et al. [24] showed that the maximum power dissipated by an electrical field intensity of 9.5 kV/mm is 9 times greater than that transferred in the absence of an electric field. Maximum temperature of the evaporator decreases significantly under the action of an electric field. Thus, for a power of 2.5 W, the maximum evaporator temperature decreases from 72 °C for an electric field intensity of 4 kV/mm, to 57 °C for an electric field intensity of 8 kV/mm. Theoretical calculations are performed by Yu et al. [18] to simulate the influence of the groove width on the maximum power transferred by the FMHP in the absence and in the presence of an electric field. Increasing the width of the groove combined with the action of the electric field (intensity equal to 8 kV/mm) can significantly increase the maximum power transferred by the FMHP.

The few studies carried out until now on the EHD effects on the FMHP thermal performances have rather experimental vocation.