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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 reduces the dry-out when the applied heat input is higher than the capillary limit.

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# 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.

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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

$$\Delta P_{\text{EHD}} + \Delta P_c \Delta P_v + \Delta P_l + \Delta P_g \tag{1}$$

where  $\Delta P_{EHD}$  and  $\Delta P_c$  are the electrohydrodynamic and the capillary pressures, respectively.  $\Delta P_l$  and  $\Delta P_v$  are the pressure losses in the liquid and vapor phases, respectively.  $\Delta P_g$  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

dmicrochannel side, electrode spacing, miinagent vector to the liquid-vapor interface $D_g$ groove height, mvvelocity, m/s $P_h$ hydraulic diameter, mVvelocity, m/s $e$ liquid height between the electrodes, mV $V_g$ groove width, m $E_n$ electric field strength for the horizontal electrode arrangement, V/m $Creek symbols$ $F_n$ electric field strength for the vertical electrode arrange- ment, V/m $Creek symbols$ $f_i$ interfacial electric field strength for the vertical electrode arrange- ment, V/m $Ah_h$ height difference, m $f_i$ interfacial electrod force per unit of length, N/m $AP_{crop}$ $Creek symbols$ $F_c$ columb force per unit of length, N/m $AP_{crop}$ $Ah_h$ height difference, m $f_i$ interfacial liquid-vapor shear force per unit length, N/m $AP_{crop}$ $AP_{crop}$ $AP_{crop}$ $F_{in}$ interfacial liquid-vapor shear force per unit length, N/m $AP_{crop}$ $AP_{crop}$ $AP_{crop}$ $F_{w}$ vapor shear force per unit length, N/m $A_{p}$ idquid pressure drop, N/m <sup>2</sup> $F_{w}$ vapor shear force per unit length, N/m $a_{p}$ $absolute dielectric permittivity of vacuum, F/mF_{w}vapor shear force per unit length, N/ma_{p}absolute dielectric permittivity of vacuum, F/mF_{w}vapor shear force per unit length, N/ma_{p}adiabaticF_{w}vapor shear force per unit length, N/ma_{p}adiabaticF_{w}$	А	area. m <sup>2</sup>	Т	temperature. °C
$ \begin{array}{cccc} D_p & groove height, m & v & velocity, m/s & mapping to point the point of the point $	d	microchannel side, electrode spacing, m	ī	tangent vector to the liquid-vapor interface
	Dα	groove height, m	v	velocity. m/s
	D <sub>b</sub>	hydraulic diameter. m	V	voltage. V
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	Ē.	electric field between two electrodes V/m	L	
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$ \begin{array}{llllllllllllllllllllllllllllllllllll$	I <sub>S</sub> F	alactric force per unit of volume N/m <sup>3</sup>	$\Delta P_c$	capillary pressure, N/m <sup>2</sup>
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	I <sub>V</sub> Г	Coulomb force per unit of length N/m	$\Delta P_{EHD}$	electrohydrodynamic pressure, N/m <sup>2</sup>
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	г <sub>с</sub> г	dialactrophoratic force per unit length N/m	$\Delta P_g$	hydrostatic pressure, N/m <sup>2</sup>
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	г <sub>diel</sub>	interferiel liquid years cheer force per unit length N/m	$\Delta P_1$	liquid pressure drop, N/m <sup>2</sup>
$\begin{array}{llllllllllllllllllllllllllllllllllll$	Г <sub>і</sub> Г	interfactal inquid-vapor shear force per unit length, N/m	$\Delta P_v$	vapor pressure drop, N/m <sup>2</sup>
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$p_i$ perimeter of the liquid-vapor interface, miinterfacial $p_1$ coefficient defined in Eq. (33)ilinterfacial (liquid side) $p_{lw}$ perimeter of the liquid-wall interface, mivinterfacial (vapor side) $p_{vw}$ perimeter of the vapor-wall interface, mlliquidPpressure, N/m²lwliquid-wallPoPoiseuille numbermaxmaximum $q_s$ surface density of the electrical charges, C/m²minminimum $q_v$ volume density of the electrical charges, C/m³nnormalQheat input power, Wsatsaturation $Q_a$ axial heat flux rate, Wttangential $r_1$ , $r_2$ principal curvature radii of an interface, mvvapor, vertical $r_c$ curvature liquid-vapor interface radius, mvwwallReReynolds numberwwall	Ng	groove number	h	horizontal
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$p_{Iw}$ perimeter of the liquid-wall interface, mininterfacial (input office) $p_{vw}$ perimeter of the vapor-wall interface, mivinterfacial (vapor side)Ppressure, N/m²lliquidPoPoiseuille numberlwliquid-wallqssurface density of the electrical charges, C/m²maxmaximumqvvolume density of the electrical charges, C/m³nnormalQheat input power, WsatsaturationQaaxial heat flux rate, Wttangentialr1, r2principal curvature radii of an interface, mvvapor, verticalrccurvature liquid-vapor interface radius, mvwvapor-wallReReynolds numberwwall	pı	coefficient defined in Eq. (33)	il	interfacial (liquid side)
$p_{vw}$ perimeter of the vapor-wall interface, m $i$ liquidPpressure, N/m²lliquid-wallPoPoiseuille numberlwliquid-wallqssurface density of the electrical charges, C/m²maxmaximumqvvolume density of the electrical charges, C/m³nnormalQheat input power, WsatsaturationQaaxial heat flux rate, Wttangentialr1, r2principal curvature radii of an interface, mvvapor, verticalrccurvature liquid-vapor interface radius, mvwvapor-wallReReynolds numberwwall	$p_{lw}$	perimeter of the liquid-wall interface, m	iv	interfacial (vapor side)
Ppressure, N/m²IIquidPoPoiseuille numberIwliquid-wallqssurface density of the electrical charges, C/m²maxmaximumqvvolume density of the electrical charges, C/m³nnormalQheat input power, WsatsaturationQaaxial heat flux rate, Wttangentialr1, r2principal curvature radii of an interface, mvvapor, verticalrccurvature liquid-vapor interface radius, mvwvapor-wallReReynolds numberwwall	$p_{vw}$	perimeter of the vapor-wall interface, m	1	liquid
PoPoiseuille numbernwinduct wantqssurface density of the electrical charges, C/m²maxmaximumqvvolume density of the electrical charges, C/m³nnormalQheat input power, WsatsaturationQaaxial heat flux rate, Wttangentialr1, r2principal curvature radii of an interface, mvvapor, verticalrccurvature liquid-vapor interface radius, mvwvapor-wallReReynolds numberwwall	Р	pressure, N/m <sup>2</sup>	1	liquid-wall
$q_s$ surface density of the electrical charges, $C/m^2$ maxmax $q_v$ volume density of the electrical charges, $C/m^3$ minminimum $Q$ heat input power, Wsatsaturation $Q_a$ axial heat flux rate, Wttangential $r_1, r_2$ principal curvature radii of an interface, mvvapor, vertical $r_c$ curvature liquid-vapor interface radius, mvwvapor-wallReReynolds numberwwall	Ро	Poiseuille number	may	maximum
$q_v$ volume density of the electrical charges, C/m³Immon mormalQheat input power, Wnnormal $Q_a$ axial heat flux rate, Wsatsaturation $r_1, r_2$ principal curvature radii of an interface, mvvapor, vertical $r_c$ curvature liquid-vapor interface radius, mvwvapor-wallReReynolds numberwwall	qs	surface density of the electrical charges, C/m <sup>2</sup>	min	minimum
Qheat input power, WnnonnanQaaxial heat flux rate, Wsatsaturationr1, r2principal curvature radii of an interface, mvvapor, verticalrccurvature liquid-vapor interface radius, mvwvapor-wallReReynolds numberwwall	q <sub>v</sub>	volume density of the electrical charges, C/m <sup>3</sup>	n	normal
Qaaxial heat flux rate, Wsatsaturationr1, r2principal curvature radii of an interface, mttangentialrccurvature liquid-vapor interface radius, mvvapor, verticalReReynolds numberwwall	Q	heat input power, W	II cat	saturation
r1, r2principal curvature radii of an interface, mvvapor, verticalrccurvature liquid-vapor interface radius, mvwvapor-wallReReynolds numberwwall	Qa	axial heat flux rate, W	sai t	tangential
r <sub>c</sub> curvature liquid-vapor interface radius, m vw vapor-wall Re Reynolds number w wall	г <sub>1</sub> , г <sub>2</sub>	principal curvature radii of an interface, m	L V	Langential
Re Reynolds number w wall	r <sub>c</sub>	curvature liquid-vapor interface radius, m	V	vapor, vertical
- vv vvdii	Re	Reynolds number		vapor-wan wall
		-	vv	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.

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