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Effect of electric field on the enhanced heat transfer characteristic of an evaporator with multilayered sintered copper mesh

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ABSTRACT

In this paper, it was investigated experimentally that the effect of different kinds of working fluid on the thermal performance of evaporator with capillary wick consisted by multilayered sintered copper mesh under different electric field strengths at the operating pressure of 1.01×10^5 Pa R141b and R123 were used as the working fluids. The electric field strength in this study was in the range of 0kV/m–1600 kV/m, respectively. The experimental results showed that the applied electric field strength has significant effect on heat transfer characteristic. The heat transfer enhancement effects increased with the increase of the electric field. Under the applied electric field strength, the maximum heat transfer enhancement factors could reach as high as 1.5 and 1.32 for the two kinds of working fluids in the experiment.

Introduction

The enhancement of boiling heat transfer is very important for the thermal management of electronic devices. High temperature may cause degradation in the performance of electronics and premature failure. Developing a high intensity heat dissipating system at the micro scale is of significance for meeting not only the performance requirements, but reliability requirements as well. Heat pipes have excellent performance in efficient heat transport area and have shown promise for passive thermal management of electronic devices. The capillary force developed by wick structure circulates the fluid. Therefore, the capillary pumping capacity is a primary limitation governing the operation of these devices. Heat pipes, in particular, have very limited pumping capability. Conventional heat pipes, in particular, due to the large viscous losses, have very limited pumping capability. Electrohydrodynamic (EHD) pumping has many advantages, such as simple design, nonmechanical, low acoustic noise, lightweight, rapid control of performance, and low power consumption, which are the most important. EHD pumping can be used for heat transfer enhancement of heat pipes. A number of experimental investigations have been made to understand the heat transfer characteristics of the vapor–liquid phase change process under electric field strength [1–8].

Some researchers have attempted to enhance the heat transfer process of a heat pipe using EHD phenomena. Jones [9] replaced the capillary wicking structure in a heat pipe with an electrohydrodynamic pump, which utilizes polarization EHD force effects to provide a net liquid pumping force to replace the capillary wick of conventional heat pipe. Jones and Perry [10] designed an EHD heat pipe successfully, which employed an electromechanical flow structure for axial liquid flow structure and a capillary wicking structure. The experimental results showed that the electromechanical flow structure provides improved performance over the felt-metal wick structure for power levels of approximately 25 W and up, while for 20 W the capillary is sufficiently by itself. Loehrke and Debs [11] improved the electrohydrodynamic (EHD) heat pipe of Jones and Perry and were able to achieve equivalent thermal performance of conventional axial-groove heat pipes. Bologa and Savin [12] used the dielectrophoretic force to enhance the heat transport capacity in an experimental heat pipe operating as a two-phase thermosiphon and obtained 53% increase in the heat transport capacity after using 36 kV. An ion-drag pump was constructed and calibrated to determine the available pumping pressure as a function of input voltage for various working fluids by Babin et al. [13]. The experimental results were then compared with an analytical model and found to predict the ion-drag pump performance to within ±15%. The performance enhancement of the

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Nomenclature

a	enhancement coefficient
E	the electric field strength
g	gravitational acceleration, (m/s^2)
q	heat flux density, (W/m^2)
l	distance between two thermocouples, (m)
h	heat transfer coefficient, (W/(m^2 K))
h_c	capillary height
h_{EHD}	the evaporation/boiling heat transfer coefficient with the applied electric field
h_0	the evaporation/boiling heat transfer coefficient without the applied electric field
ΔP	electrostatic pressure
T_t	the temperature of the copper plate with micro-channels, (K)
T_s	the saturation temperature of the working fluid, (K)
T_1, T_2, T_3, T_4	the temperature of the copper heater, (K)
λ	the thermal conductivity of the pure copper, (W/(m K))
ε_l	permittivity of liquid
ε_g	permittivity of gas
ρ	the liquid density
ρ_c	space charge density

thermal test loop ranged from 20 to 100% was determined, due to the addition of a two-stage ion-drag pump. Balram [14] presented a model for the fluid flow and heat transfer in a electrohydrodynamic augmented micro heat pipe. The analytical result showed that with an increase in electric field intensity, the critical heat input increases and the dryout length decreases. It is found that using EHD, the critical heat input can be increased by 100 times. The critical heat input and the dryout length have been compared successfully with the experimental results available in the literature. Melcher [15] gave a discussion on the phenomena that dielectric liquid tended to fill the region where the electric field is the strongest. Bryan and Seyed-Yagoobi [16] investigated experimentally on the enhancement of the heat transport of a monogroove heat pipe with electrohydrodynamic (EHD) pumping. The fluid used in the experiment was R123. The experimental results showed that over 100% enhancement in the transport capacity was achieved using the EHD pump operating at 20 kV. Yu et al. [17] conducted an experimental study to evaluate the potential benefits of electrohydrodynamic forces on the operation of micro heat pipes. The experimental result indicated the heat transport capability of the EHD micro heat pipes is increased by up to six times of that for conventional one. In addition, Jeong and Seyed-Yagoobi [18] performed an experimental investigation to clarify the EHD pumping mechanism and improved the heat transport capacity with an proper electrode design. Mo et al. [19] performed an experimental study to characterize the start-up process for an EHD-assisted capillary pumped loop (CPL) system. An EHD-assisted evaporator with 1500 W of the maximum allowable heat transport capacity was used with a spring-type electrode inserted into the liquid channel of the evaporator. Their experimental data showed that the EHD can reduce the start-up time by as much as 50% at an applied voltage of 10 kV and a power level of 10 W with R-134a as the working fluid. The start-up time reduction for 20 W and 50 W power levels were 30% and 20%, respectively. Darabi et al. [20] studied the feasibility of combining micro fabrication technology with the EHD technique for high heat-flux electronic cooling applications. The device incorporates an active evaporative cooling surface, a polarization micropump, and temperature sensors in a single chip. Its prototype device demonstrated a maximum cooling capacity 65 W/cm^2 with a corresponding pump head of 250 Pa. Darabi et al. [21] carried out an experimental investigation to develop a MEMS-based micro cooling device to provide direct cooling to high heat flux electronics and MEMS devices. This device uses the electrohydrodynamic principles to pump and form an ultra thin film over a heated surface that requires cooling. HFE-7100 thermal fluid was used as the working fluid. Cooling rates of 35 W/cm^2 were obtained at a superheat of 19 °C. Lackowski et al. [22] studied the effect of the electric field and its frequency on the flow rate of 2-propanol flowing under constant hydrostatic pressure through a microchannel. The experimental results show that the control of liquid flow in the microchannel is possible with alternating electric field of properly tuned frequency and adequate voltage. Wang et al. [23] investigated optimal heat transfer performance of Electrospray evaporative cooling (ESEC) chambers with different geometry types. The experimental results show that for the same kind of ESEC chamber, the heat transfer performance at different heat fluxes is distinct. At the same heat flux, the enhancement ratio increases when the working fluid flow rate and applied potential are increased. Pearson and Yagoobi [24] investigated the pressure and flow generation performance for both a meso-scale and a micro-scale conduction pump by using HCFC-123 as the working fluid. The experimental results show that both pumps could provide significant pressure and flow rates. Xu [25] applied He's parameter-expansion method (PEM) to a nonlinear oscillation of a mass attached to a stretched wire. Esmaeilpour et al. [26] employed the homotopy perturbation method (HPM) to the problem of forced convection over a horizontal flat plate to compute an approximation to the solution of the system of nonlinear differential equations governing the problem.

As the literature survey mentioned above, the application of an electric field in two-phase systems could enhance liquid–vapor system heat transfer process. In this paper, refrigerant R141b and R123 were employed as working fluid to study the phase change heat transfer characteristic for vertical plate with sintered copper mesh under a saturated vapor ambient at operating pressure of 1.01×10^5 Pa. A significant heat transfer enhancement for the sintered copper mesh surface was obtained under applied electric field strength compared with zero electric field strength. The electric field force exerted on the fluid is responsible for the heat transfer enhancement of R141b and R123 on the plate with multilayered sintered copper mesh.

Electric field and electrohydrodynamic effects

From the electrohydrodynamics (EHD) theory [27], the electrical force density f_e exerted on the fluid can be generally expressed by

$$f_e = \rho_c E - \frac{1}{2}E^2\nabla\varepsilon + \frac{1}{2}\nabla\left(\rho E^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T\right) \tag{1}$$

where ρ_c, E, ε and ρ are space charge density, the electric field strength, the permittivity and the liquid density. The first term on the right hand side of Eq. (1), known as the Coulomb force, acts on the free charges in the fluid. The second term is due to the gradient in the dielectric permittivity at the phase interface. The third term is the electrostriction force depending on non-uniformity of electric permittivity. In the heat transfer systems with phase change, in presence of an electric field, dielectrophoretic force due to difference in electric permittivity of liquid and vapor is the most important one. The last two terms become important in the case of EHD phenomena in liquids as well as the gas–liquid interface.

When applied an electric field on the liquid between a pair of parallel electrodes, the liquid level could rise, the mechanism could