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Thermal performance of flat micro heat pipe with converging microchannels

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ABSTRACT

Optimizing the groove size of flat micro heat pipes is crucial for improving their thermal performance. In this study, we developed a grooved converging microchannel array for use in a flat micro heat pipe to enhance the capillary force. A simplified theoretical analysis was used to optimize the groove size for given operating conditions of converging microchannels and straight microchannels. The evaporation section of the grooved microchannel was hydrophilic and had a smaller hydraulic diameter than the hydrophobic condensation section. The smaller diameter of the evaporation section enabled the condensed working fluid to be effectively drawn back to the same section. Experiments were performed to measure the thermal performance of the micro heat pipes under the analyzed operating conditions. Compared to a heat pipe with a straight microchannel, and a heat pipe with an unoptimized converging microchannel, the micro heat pipe with the optimized converging microchannel was confirmed to yield a higher thermal performance. Capillary-driven flow experiments at room temperature and atmospheric pressure were also used to investigate the capillary forces of the different microchannels. The optimized converging microchannel was once again observed to generate the largest capillary force.

1. Introduction

Micro heat pipes (MHPs) are self-driven cooling devices used for the removal of high heat flux from electronic devices. They can be fabricated using micro-electro-mechanical system (MEMS) technology, and considerable research has been channeled toward developing innovative MEMS-based flat micro heat pipes [1–20]. Although the compactness of flat MHPs is well-suited to the cooling of current and future chips, their thermal performance is limited by miniaturization. To improve the thermal performance of flat MHPs, a better understanding of the associated heat and mass transfer phenomena is required.

The capillary limit is a major challenge in improving the thermal performance of a flat MHP and avoiding dry-out in its evaporation section. In a flat MHP, the liquid returns from the condenser to the evaporator through a capillary structure that is usually composed of a microchannel array, which differs from the additional wicks installed in a conventional heat pipe. Accordingly, the capillary radius of the liquid–vapor interface in an MHP is comparable to the hydraulic diameter of the flow passage, and the capillary action dominates the gravitational force in the microchannel array. The capillary limit of an MHP thus depends on the capillary performance of the microchannel.

Several studies on capillary-driven flow have investigated the capillary performance of microchannels [21–40]. It has been found that the capillary force can be increased by decreasing the characteristic length, i.e., the hydraulic diameter, of the microchannel grooves [25–30], and controlling the surface structure [31–34] or wettability [35–37]. However, the pressure drop due to viscous friction in microchannels increases with the decreasing hydraulic diameter of the flow passage. Yang et al. reported that capillary filling of a nanochannel significantly degrades the performance [38]. Conversely, given the relatively high surface-to-volume ratio of a microchannel, the surface effect increases with the decreasing scale of the channel [41–44]. Nagayama et al. posited that the scale effect of the solid–liquid interfacial resistance in a microchannel becomes more significant with a decreasing hydraulic diameter [44]. The deviation from the classical theory with a decreasing hydraulic diameter is due to a breakdown of the continuum solid–liquid boundary condition. In addition, the hydraulic and thermal resistances are the dominant causative factors of the poor thermal performance of microchannels. Optimization of the groove size is thus crucial to enhancing the thermal performance of a flat MHP.

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Nomenclature

A	area, m^2
A_1	cross-sectional area of vapor, m^2
h	heat transfer coefficient, W/(m^2·K)
h_{fg}	latent heat, J/kg
H	groove height, m
N	number of grooves, -
L	length, m
$\dot{m}$	mass flow rate, kg/s
p	pressure, N/m^2
Q	input heat, W
R	thermal resistance, K/W
t	time, s
T	temperature, K
u	velocity, m/s
W	groove width, m

Greek symbols

θ	contact angle, degree
λ	thermal conductivity, W/(m·K)
μ	viscosity, Pa·s
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

c	condenser section
ca	capillary
e	evaporator section
hp	heat pipe
i	liquid–vapor interface
l	liquid
v	vapor

In the present study, we developed a novel grooved converging microchannel array for a flat MHP to enhance the thermal performance [45]. To effectively draw the condensed working fluid back into the evaporation section of the microchannel, the hydraulic diameter of the grooves in the condensation section was made larger than that of the grooves in the evaporation section. The optimal groove size was determined based on the balance between the capillary and frictional forces in the rectangular grooves, taking into consideration the effect of surface wettability. Experiments were performed to compare the maximum input heat of the optimized converging microchannel with that of a straight microchannel. The heat pipe with the optimized converging microchannel was confirmed to exhibit a higher thermal performance. Experiments were also performed to clarify the effect of convergence on the force of the capillary-driven flow at room temperature and atmospheric pressure.

2. Theoretical model

Fig. 1 shows a schematic of the open rectangular groove considered in this study. The groove height H and length L are constant, whereas the width $W(x)$ linearly decreases in the x-direction. The groove has a converging shape, with the cross-sectional area decreasing in the axial direction between the condensation and evaporation sections.

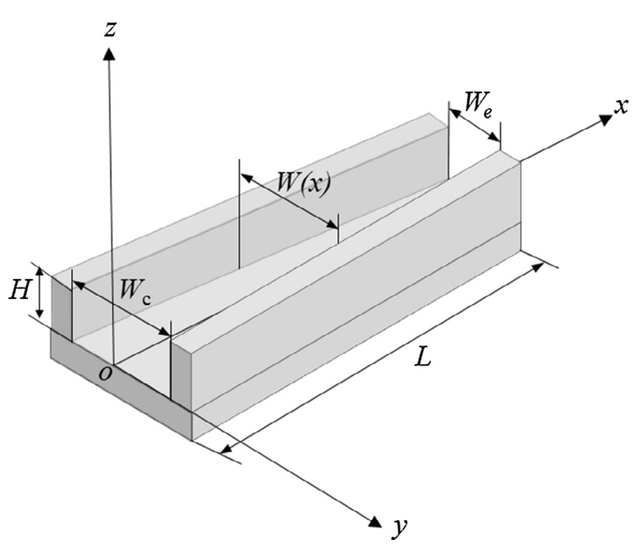

Fig. 1. Model of a groove in the converging microchannel array for a flat micro heat pipe.

To optimize the groove size of the flat heat pipe, the balance between the capillary force and the pressure loss of the flow along the x-axis of the microchannel was derived based on the following assumptions:

(1) steady-state incompressible flow,
(2) saturated vapor,
(3) negligible heat generation due to viscous dissipation,
(4) no dry-out in the evaporation section, and
(5) no blocking in the condensation section.

The local physical properties of the liquid and vapor along the x-axis were considered temperature-dependent variables.

2.1. Capillary force

When a meniscus is formed at the liquid–vapor interface inside the groove, the local pressure difference at the interface at x, $\Delta p_i(x)$, can be calculated by the well-known Young–Laplace equation:

$$\Delta p_i(x) = \Delta p_v(x) - \Delta p_l(x) = \sigma_l(x)\cos\theta \cdot \left(\frac{1}{W(x)/2} + \frac{1}{H}\right), \quad (1)$$

where $\sigma_1(x)$ is the local surface tension of the liquid, and θ is the local contact angle of the meniscus.

Because the groove height H and length L are constant, a decrease in the groove width would increase the capillary pressure, according to Eq. (1). To effectively draw the condensed working fluid back into the evaporation section, the minimum groove width should be the optimized value for the evaporation section, resulting in the maximization of Eq. (1), while the maximum width should be the optimized value for the condensation section. The local pressure differences at the liquid–vapor interfaces in the condensation and evaporation sections are respectively given by

$$\Delta p_i(0) = \sigma_c \cos\theta_c \cdot \left(\frac{W_c + 2H}{W_c H}\right) \quad (2)$$

and

$$\Delta p_i(L) = \sigma_e \cos\theta_e \cdot \left(\frac{W_e + 2H}{W_e H}\right), \quad (3)$$