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Effect of channel geometry on the operating limit of micro pulsating heat pipes

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ABSTRACT

In the present study, the operating limit of micro pulsating heat pipes (MPHPs) was investigated with different channel geometries: cross-sectional shapes and hydraulic diameters. Five-turn closed-loop MPHPs, which have either circular or square channels with hydraulic diameters of 390, 480, and 570 μm, were fabricated onto a silicon wafer using MEMS techniques. To allow flow visualization, a transparent glass wafer was bonded to the silicon wafer. FC-72 was used as the working fluid with a filling ratio of 50%. Experimental results show that the operating limit, where the thermal performance significantly deteriorates, increases with the hydraulic diameter in both cross-sectional shapes. At the same hydraulic diameter, the square-channel MPHP can handle approximately 70% higher maximum allowable heat flux than the circular-channel MPHP. Based on the results of flow visualization, a model for the operating limit of the MPHPs in a vertical orientation was proposed: It was postulated that the MPHPs reach the operating limit when the falling film flow rate is smaller than the evaporation rate at any instant the liquid film is formed. This postulate was experimentally confirmed by comparing two rates for various channel geometries. Finally, a correlation for predicting the maximum allowable heat flux of the MPHPs was developed using a scale analysis and experimental data. According to the model, the maximum allowable heat flux is found to be proportional to the third power of the hydraulic diameter regardless of the cross-sectional shape.

1. Introduction

Conventional heat pipes have been widely used for the cooling of electronic devices. However, for thin and flexible electronic devices currently under development, a new cooling device is needed because the conventional heat pipes afford limited flexibility in terms of shape due to the wick structure. A pulsating heat pipe (PHP), which was first introduced by Akachi et al. [1], is considered a promising cooling device to satisfy this new requirement. The PHP consists of a small, serpentine channel without any wick structure. Previous studies reported that PHPs had two operating modes depending on the input heat flux [2–4]. After the startup of an oscillation, the flow pattern changed from the oscillation mode to the circulation mode with increasing input heat flux. When the input heat flux increased further above the maximum allowable heat flux, it was observed that the operating limit occurred with a noticeable deterioration of the thermal performance [5–7].

Previous researchers have investigated the operating limit of PHPs to determine their applicable range of input power or heat flux. Yang et al. [5] experimentally compared the operating limits of PHPs for various tube diameters, filling ratios, and inclination angles. They reported that the operating limit was characterized by the dryout phenomenon in the evaporator section. Kammuang-Lue et al. [6] proposed an empirical correlation for predicting the maximum total heat flux of PHPs. A dry patch in their glass-based PHP was observed while it was operating in the circulation mode. They reported that when the working fluid passed through the evaporator section in the uni-directional flow, slug flow changed to annular flow due to an increase in the vapor velocity with increasing input heat flux and the liquid film in the annular flow finally dried above the maximum allowable heat flux. However, Qu et al. [7] reported that dryout occurred in the oscillation mode before reaching the circulation mode. The circulation mode was not observed in their micro pulsating heat pipes (MPHPs) with hydraulic diameters of 251 and 352 μm. Manzoni et al. [8] mentioned that MPHPs were difficult to operate in the circulation mode because of an increase in the frictional pressure drop with decreasing hydraulic diameter. Therefore, it is necessary

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Nomenclature

a	acceleration of the meniscus [m/s^2]
A	area [m^2]
Bo_{acc}	Bond number based on the acceleration of the meniscus, $Bo_{acc} = \rho a D^2/\sigma$ [–]
C	empirical constant [–]
Ca	capillary number, $Ca = \mu U/\sigma$ [–]
D_h	hydraulic diameter [m]
g	gravitational acceleration [m/s^2]
h_{lv}	latent heat [J/kg]
L	length [m]
$\dot{m}_e$	evaporation rate [kg/s]
Q	heat rate [W]
q''	heat flux [W/m^2]
q''_{max}	maximum allowable heat flux [W/m^2]
R_{th}	thermal resistance [K/W]
Re	Reynolds number, $Re = \rho U D/\mu$ [–]
r	radius [m]
$\bar{T}$	average temperature [°C]
u	velocity along the x-direction [m/s]
U	velocity of the meniscus [m/s]
v	velocity along the y-direction [m/s]
x	x-direction coordinate
y	y-direction coordinate

Greek symbols

Γ	film flow rate [kg/s]
δ	liquid film thickness [m]
θ	angle [°]
μ	viscosity [Pa·s]
ρ	density [kg/m^3]
σ	surface tension [N/m]

Subscripts

c	condenser
cir	circular-channel MPHP
crit	critical
e	evaporator or evaporation
in	total input
l	liquid phase
sqr	square-channel MPHP
v	vapor phase

to propose a new correlation for predicting the maximum allowable heat flux of a PHP when it operates in the oscillation mode.

The purpose of the present study is to determine the criterion for the operating limit of a PHP in the oscillation mode. For this purpose, five-turn closed-loop MPHPs, which have either circular or square serpentine channels with hydraulic diameters of 390, 480, and 570 μm, were fabricated onto a silicon wafer. To allow flow visualization, a transparent glass wafer was bonded to the silicon wafer. Experimental investigations into the effect of the channel geometry on flow and heat transfer characteristics were performed through high-speed photography and thermometry. Based on the experimental observations, a model for the operating limit was proposed and validated. Results from the model were used to develop a correlation for predicting the maximum allowable heat flux of MPHPs with circular or square channels.

2. Experiments

2.1. Fabrication of MPHPs

To fabricate the five-turn closed-loop MPHPs with different channel geometries, the MEMS techniques were used. To fabricate the square-channel MPHP, microchannels with a square cross section were etched onto a silicon wafer with a thickness of 1 mm using a deep reactive ion etching (DRIE) process. To fabricate the circular-channel MPHP, microchannels with a semi-circular cross section were etched onto a silicon wafer and a glass wafer (#7740 PyrexTM). Xenon difluoride (XeF_2) etching was used for the silicon wafer, while hydrofluoric (HF) wet etching was used for the glass wafer. The glass wafer was anodically bonded to the silicon wafer for both cross-sectional shapes to allow flow visualization. Two holes were also etched onto the silicon wafer to charge FC-72 (Fluorinert liquid FC-72, 3M), which was used as the working fluid. Degassing and charging processes of the working fluid were performed, as explained by Youn and Kim [9]. The fabricated MPHP, which was filled with the working fluid (bright parts: liquid slugs, dark parts: vapor plugs), and the cross sections of the circular-channel MPHP and the square-channel MPHP are shown in Fig. 1, respectively. The filling ratio, which was defined

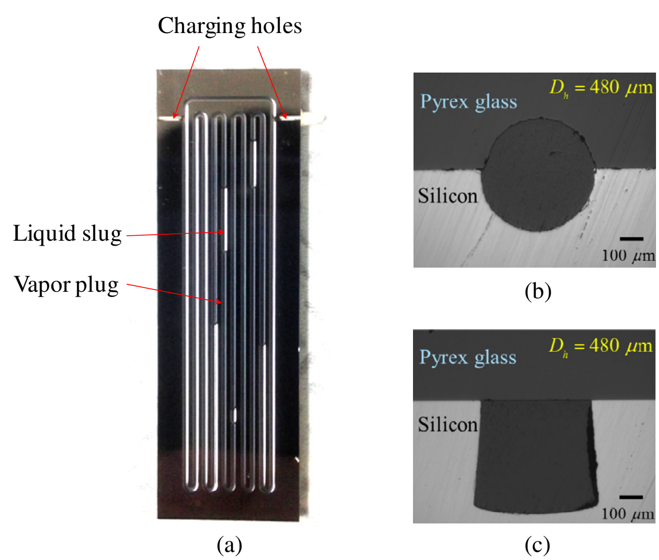

Fig. 1. Photographs of the (a) fabricated MPHP filled with FC-72 (bright parts: liquid slugs, dark parts: vapor plugs) and cross sections: (b) circular-channel and (c) square-channel MPHPs.

as the ratio of charged liquid volume to total channel volume, was fixed at 50%. Fig. 2 presents temperature measurement points and locations of the evaporator, adiabatic, and condenser sections. The experimental parameters used in the present study are shown in Table 1.

2.2. Experimental setup

Fig. 3 shows a schematic of the experimental setup for evaluating the thermal performance of the MPHPs. A Nichrome target (Ni: Cr = 80:20 wt%, I-Nexus) was evenly sputtered on the silicon surface to create a very thin heater in the evaporator section. An electric current was applied to the heater from a DC power supply (N5772A, Agilent Technologies). The wall temperatures were