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Experimental investigation on the thermal performance of a micro pulsating heat pipe with a dual-diameter channel

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Experiments were performed to investigate the effect of a dual-diameter channel on the flow and heat transfer characteristics of flat plate micro pulsating heat pipes (MPHPs). Using MEMS techniques, the MPHPs were fabricated: rectangular channels with dual hydraulic diameters were engraved on a silicon wafer to form a meandering closed loop with 5 turns. The Pyrex glass was used as a cover which enables flow visualization in the MPHP. Experimental results show that the MPHPs with a dual-diameter channel can operate stably even in a horizontal position and have uniform thermal performance regardless of the orientation when a proper condition is met. It is postulated that the orientation-independent performance occurs when the capillary pressure generated by the difference in channel diameters is larger than the viscous pressure drop. This postulate was experimentally confirmed using Ethanol and FC-72 as working fluids at various input powers and inclination angles. To provide a guideline for orientation-independent operation of the MPHP with a dual-diameter channel a figure of merit is proposed: the figure of merit is defined as the ratio of capillary pressure difference to the viscous pressure drop, which is similar to the figure of merit for a conventional heat pipe. According to experimental data, the figure of merit has to be larger than 2×10^5 for orientation-independent operation of the MPHP.

1. Introduction

The decrease in the size of electronics and the advances in processor speed have led to a rise in heat flux and generate hot spots on a chip [1]. Thus, the demand for effective heat transfer devices has increased, and various types of heat pipes have been studied extensively [2]. However, the wick structure of conventional heat pipes has been the obstacle to thermal management of very thin electronic devices because it is inappropriate for miniaturization. As a wickless heat pipe, micro pulsating heat pipes (MPHPs) are a promising candidate for implementation in microelectronics cooling owing to their simple design which consists of a small and long meandering tube [3].

Because small electronic devices, such as smart phones, tablet computers, and laptops, are used in various poses and orientations, MPHPs for portable devices have to guarantee orientation-independent thermal performance. The dependence of thermal performance on the orientation is known to be strongly coupled to the number of turns. While PHPs with many turns (20 turns or more) exhibit stable thermal performance regardless of the inclination angle, PHPs with only a few turns show worse thermal performance or do not operate at all in a horizontal position [4]. This is also the case for the MPHPs because MPHPs developed by previous investigators [1,3,4–6] have just a few turns. To ensure operation of PHPs in a horizontal position, Chien et al. [7] developed a flat plate PHP which has 16 alternating size of parallel square channels with cross-sections of 2 mm × 2 mm and 1 mm × 2 mm. Their results showed that the PHP with a uniform channel was not functional in a horizontal position whereas the PHP with a dual-diameter channel was functional in the horizontal arrangement. Their PHP with a dual-diameter channel had at least 30% higher thermal resistance in a horizontal position than in a vertical position. In addition, the operating range of the PHP in a horizontal position was also much narrower than that in a vertical position. Then a question arises as to orientation-independent performance: is it possible to design a PHP whose performance does not vary with the inclination angle?

Our earlier work [8] may provide a clue to answering this question. We observed that there existed an optimal dimensionless diameter difference for which the thermal performance of a single-turn PHP was maximized. The capillary force which is induced by capillary pressure difference in a dual-diameter channel increases with either by increasing the diameter difference or by decreasing the average channel diameter of a dual-diameter

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Nomenclature

A_c	cross sectional area [m^2]
Bo	boiling number [–]
C_f	friction coefficient [–]
Ca	capillary number [–]
D_h	hydraulic diameter [m]
f	friction factor [–]
g	gravitational acceleration [m/s^2]
h	channel height [m]
I	electric current [A]
k_{eff}	effective thermal conductivity [W/m K]
L	length [m]
L_{eff}	effective length [m]
N_t	total number of pair of channels [–]
N	number of dual-diameter pairs [–]
P	pressure [N/m^2]
p_w	perimeter [m]
Q_{in}	supplied input power [W]
R_{th}	thermal resistance [K/W]
Re	Reynolds number [–]
$\bar{T}$	average temperature [°C]
U	superficial velocity [m/s]
V	electric voltage [V]
w	channel width [m]
x	vapor quality [–]
z	distance [m]

Greek symbol

ρ	density [kg/m^3]
β	fraction of channel length occupied by the liquid slugs [–]
θ	inclination angle [°]
θ_c	contact angle [°]
μ	viscosity [Pa s]
σ	surface tension [N/m]

Subscripts

1	larger channel
2	smaller channel
a	adiabatic
c	condenser
ca	capillary
e	evaporator
l	liquid phase
v	vapor phase

channel. If the working fluid is Ethanol or FC-72, the capillary force induced by a dual-diameter channel becomes comparable to the gravitational force when the channel diameter is several hundred micrometers or smaller. Therefore, if a PHP is fabricated to have a dual-diameter channel with an optimal diameter difference and hydraulic diameters of several hundred micrometers, it can have orientation-independent performance with smaller thermal resistance.

The purpose of the present study is to provide design guidelines for orientation-independent operation of the MPHP with a dual-diameter channel. Using MEMS techniques, the MPHPs were fabricated: a rectangular channel with dual hydraulic diameters was engraved on a silicon wafer to form a meandering closed loop with 5 turns. To find the optimum range of the difference in channel hydraulic diameters, experimental investigations into the effect of a dual-diameter channel on flow and thermal characteristics of MPHPs were performed with high-speed photography and thermometry. To allow visualization of the internal flow behavior, the MPHPs were covered by glass wafer. Finally, based on the experimental observations, a figure of merit was proposed to provide a guideline for orientation of the MPHP with a dual-diameter channel: the figure of merit is defined as the ratio of capillary pressure difference to the viscous pressure drop, which is similar to the merit number for a conventional heat pipe.

2. Experiments

2.1. Fabrication of the MPHP

To evaluate the effect of diameter difference on operating characteristics of the MPHP, several types of MPHP were fabricated, as summarized in Table 1. The MPHP had interconnected rectangular channels of 0.5 mm height forming a meandering closed-loop engraved on a silicon wafer with thickness of 1 mm. The Pyrex glass wafer (#7740 PyrexTM) with thickness of 0.5 mm was used as a cover which enables flow visualization in the PHP. In this study, the average channel width (w_{avg}) was fixed at 1 mm to maintain both the overall width of the PHP and the number of turns. Fig. 1 shows the fabricated MPHP which had length of 50 mm, width of 18.5 mm, and thickness of 1.5 mm. The lengths of the evaporator, adiabatic, and condenser sections were 10 mm, 25 mm, and 15 mm, respectively. The MPHP had two holes for evacuation and charging the working fluid. Non-condensable gases in the working fluid in the charging chamber were removed by the degassing processes identical to those explained in the Ref. [1]. The filling ratio (defined as volume fraction occupied by the liquid in the channel at room temperature) was fixed at 50%. Ethanol and FC-72 were used as working fluids. Thermophysical properties of Ethanol and FC-72 were summarized in Table 2.

Table 1
Experimental parameters.

w_1 (μm)	w_2 (μm)	Depth (μm)	L_e (mm)	L_c (mm)	L_a (mm)	Working fluid	Filling ratio (%)
1000	1000						
1100	900						
1200	800						
1300	700	500	10	15	25	Ethanol, FC-72	50
1500	500						
1700	300						
1800	200						

2.2. Experimental setup

Fig. 2 shows the schematic diagram of the experimental setup. A series of experiments was performed in a vacuum chamber (10^{-2} ∼ 10^{-3} Torr) to minimize heat loss from the MPHP to environment. The evaporator section of the MPHP was heated by a thin film heater of Nichrome (Ni:Cr = 80:20 wt%, i-Nexus, Inc.) evenly deposited onto the silicon surface of the MPHP using sputtering system. The thin film heater was connected to a DC power supply (E3631,