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Understanding of the thermo-hydrodynamic coupling in a micro pulsating heat pipe

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ABSTRACT

In this study, experimental and theoretical investigations are performed to identify the thermo-hydrodynamic characteristics of a micro pulsating heat pipe (MPHP). Specifically, the relationship between the heat input and the vapor distribution observed in the MPHP is revealed. A silicon-based MPHP with five turns and a hydraulic diameter of 667 μm is fabricated using MEMS techniques. Experiments are performed, using ethanol as a working fluid at a filling ratio of 55%, in a vertical orientation with a bottom-heating mode. Flow visualization is conducted together with a temperature measurement. In the MPHP, two menisci located at both ends of each vapor plug are observed to be asymmetrically distributed: the position of one meniscus (*up-header*) is always located higher than that of the other (*down-comer*) and is linearly increased with an increasing heat input. At a critical value of the heat input, the position of the up-header meniscus reaches its upper limit and cannot be increased further. At this upper limit, the thermal performance of the MPHP reaches its maximum and cannot be increased further. This suggests that physically the (asymmetric) vapor distribution is the key factor that determines the heat transport capability of the MPHP. To theoretically explain the relationship between the heat input and the vapor distribution in the MPHP, a model for the asymmetric vapor distribution is developed. Based on the model, a correlation for predicting the positions of vapor menisci is proposed. Finally, the proposed correlation is shown to be useful for predicting the heat input at which the MPHP attains its maximum thermal performance.

1. Introduction

Thermal management of high-heat flux electronic devices has recently become one of the most challenging problems in the electronics industry. Various types of cooling devices have been suggested to provide a solution for systems with local hot spots. A pulsating heat pipe (PHP), which was first introduced by Akachi [1], has received attention in recent decades as an efficient heat transport device. For compact electronic devices, a micro pulsating heat pipe (MPHP), whose channel diameter is less than 1 mm, has been developed and its flow and thermal characteristics have been investigated extensively [2–8].

A PHP (or an MPHP) consists of a meandering capillary tube which is filled with a working fluid. A thermally-driven two-phase oscillating flow occurs inside the PHP and is known to transfer heat very efficiently. The pulsating heat pipe is a thermo-hydrodynamic system in which heat transfer and the thermally-induced motion of the working fluid are coupled to each other. To understand the flow characteristics of PHPs, flow visualization have been conducted for PHPs by many researchers [9–11]. Yang et al. [9] and Mameli et al. [10] experimentally investigated flow characteristics of a multi-turn PHP with varying levels of heat input. They reported that the volumetric vapor fraction of the 'up-header' channel, which has a net flow of the working fluid toward the condenser section of the PHP, was higher than that of the 'down-comer' channel, which has the net flow of the working fluid toward the evaporator section of the PHP [9]. According to their visualization results, the difference in the volumetric vapor fraction between two adjacent channels (up-header and down-header) increased with an increasing heat input [10].

To theoretically understand the relationship between the heat input and flow characteristics of PHPs, several theoretical and numerical studies [12–15] have been performed. Spinato et al. [12] and Yoon and Kim [13] adopted the so-called spring-mass-damper model to theoretically investigate the oscillation characteristics of the working fluid in a single-turn PHP and a multi-turn PHP, respectively. Mameli et al. [14] and Daimaru et al. [15] numerically investigated the oscillation characteristics, such as oscillation frequency, of the working fluid in PHPs.

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Nomenclature

A_c	cross-sectional area of the channel [m^2]
A_v	cross-sectional area of vapor plug [m^2]
D_h	hydraulic diameter [m]
F	force [N]
$\bar{F}$	static force [N]
$\tilde{F}$	dynamic force [N]
f_f	non-dimensional friction coefficient [–]
g	gravitational acceleration [m/s^2]
i_{lv}	latent heat of vaporization [J/kg]
L	length [m]
$\dot{m}$	mass transfer (or flow) rate [kg/s]
n_t	number of turns [–]
p_{ht}	heat transfer perimeter [m]
P	pressure [Pa]
$\bar{P}$	static pressure [Pa]
Q	heat transfer rate [W]
Q_{in}	heat input [W]
q'	heat transfer rate per unit length [W/m]
R_h	hydraulic radius [m]
R_{th}	thermal resistance [K/W]
Re	Reynolds number
T	temperature [°C]
v_r	radial velocity [m/s]
x	displacement [m]
$\dot{x}$	velocity [m/s]
$\ddot{x}$	acceleration [m/s^2]
$\bar{x}$	equilibrium position [m]
$\tilde{x}$	displacement variation from the equilibrium position [m]
y	position of vapor meniscus from bottom of channel [m]
$\bar{y}$	time-averaged position of vapor meniscus from bottom of channel [m]

Greek symbols

α	proportional factor [–]
λ	thermal conductivity [W/m·K]
μ	viscosity [Pa·s]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
τ	oscillation period [sec]

Subscripts

A	adiabatic section
C	condenser
c	cooler
cd	condensation
D	down-comer
E	evaporator
ev	evaporation
eff	effective
f	friction
g	gravity
h	hydraulic
$inertial$	inertial
l	liquid phase or liquid slug
n	liquid slug/vapor plug number
net	net
r	radial
si	silicon
U	up-header
v	vapor phase or vapor plug
$viscous$	viscous

However, it is the vapor distribution inside the PHP that controls the heat transport capability of the PHP rather than the oscillation characteristics. To the authors' knowledge, no attempt has been made to theoretically explain the relationship between the heat input and the vapor distribution.

The objective of this study is to experimentally and theoretically investigate the thermo-hydrodynamic characteristics of an MPHP. In particular, a link between the heat input and the vapor distribution inside the MPHP is sought. Using MEMS techniques, a meandering capillary channel with a hydraulic diameter of 667 μm is engraved on a silicon wafer to form a five-turn closed-loop. Experiments are conducted, using ethanol as the working fluid at a filling ratio of 55% in a vertical orientation with a bottom-heating mode. In conjunction with temperature measurement, the fluid flow in the MPHP is visualized using a high-speed camera through a transparent glass top. A relationship between the heat input and the vapor distribution in the MPHP is obtained based on a static analysis on a liquid slug. Finally, a model for predicting the asymmetric vapor distribution inside the MPHP is proposed and validated with experimental data under various working conditions (heat input and condenser temperature conditions).

2. Experiments

2.1. Fabrication of the MPHP

A meandering rectangular micro-channel was engraved on a silicon wafer to form a five-turn closed-loop. Ten interconnected parallel channels with a 1 mm width and a 0.5 mm depth were engraved on a 1 mm thick silicon wafer. To visualize the fluid flow, a 0.7 mm thick transparent glass wafer (#7740 PyrexTM) was bonded to the top surface of the wafer. Fig. 1 shows the fabricated MPHP with the overall dimensions of 50 × 18.5 × 1.7 mm^3. The length of the condenser, adiabatic, and evaporator sections were 15 mm, 25 mm, and 10 mm, respectively. Ethanol, which was used as the working fluid, was charged into the MPHP to have a fixed filling ratio (defined as the volume fraction of the working fluid in liquid phase at room temperature) of 55%. Evacuation and charging processes of the working fluid were the same as in our previous study, Ref. [13].

2.2. Experimental setup

Fig. 2(a) presents a schematic diagram of our experimental setup. All experiments were conducted in a vacuum chamber to minimize heat loss to the environment. Experiments were performed at various working conditions, such as the heat input and condenser temperature. In the evaporator section of the MPHP, a thin Nichrome film was employed to provide a constant heat flux. A DC power supply (N5772A, Agilent Technologies) was connected to the heater to supply heat inputs ranging from 2 W with increments of 2 W to a point at which the evaporator temperature was drastically increasing. The condenser section of the MPHP was cooled with cold water that was maintained at 25, 35, or 45 °C. Under each working condition, experiments were performed for more than 20 min after reaching the pseudo-steady state. Temperatures of the MPHP were measured using K-type thermocouples attached at 9 points on the silicon wall of the MPHP, as shown in Fig. 2(b). Experiments were conducted for a vertical