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Characteristics of oscillating flow in a micro pulsating heat pipe: Fundamental-mode oscillation

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ABSTRACT

Theoretical and experimental analyses are performed for oscillating flow in a micro pulsating heat pipe (MPHP). A meandering rectangular micro-channel with a hydraulic diameter of 667 μm is engraved on a silicon wafer to form a five-turn closed-loop. Flow visualization through a glass top using a high-speed camera is conducted together with temperature measurement for thermal characterization of the MPHP. The MPHP is observed to have a harmonic oscillating motion: each liquid slug in the MPHP is observed to oscillate at frequency ranging from 40 to 50 Hz with a phase difference of $2\pi/5$ between adjacent slugs. A closed-form expression for the oscillating motion of the slugs is suggested from a vapor spring-liquid mass model. To quantitatively explain the oscillating mechanism by the vapor spring, a link between the spring motion of the vapor plug and heat transfer to the vapor plug is found: Expansion and contraction of the vapor plug are shown to result from continuous evaporation and condensation at the liquid film enveloping the vapor plug. The evaporation heat transfer and the condensation heat transfer are shown to be out of phase and in turn result in a nonzero net heat transfer rate. To mathematically express the relationship between the net heat transfer rate and the spring motion of the vapor plug, a semi-analytic model is proposed. A semi-analytic expression for the vapor spring constant is developed and validated with experimental results. This study on the fundamental-mode oscillation in MPHP is expected to be used as a building block for investigating more complex oscillating motion in PHPs.

1. Introduction

Increasing the performance of electronic devices with decreasing sizes requires advancements in thermal management. A pulsating heat pipe (PHP), introduced by Akachi et al. [1], is a promising solution for cooling high heat flux electronic devices. Especially for thermal management of small and thin electronic devices, a micro pulsating heat pipe (MPHP) has been proposed as a novel heat transport device and has received a lot of attention recently [2–6].

When a meandering tube is partially filled with a working fluid, alternate vapor plugs and liquid slugs are formed inside the tube. Thermally driven oscillation of the slugs/plugs occurs in PHPs without any external power source and the oscillating 2-phase flow is known to transfer heat very efficiently. Since the thermal performance of PHPs is mainly affected by the oscillating motion of the working fluid, a thorough investigation of the oscillating motion is essential. Hence, as a first step, flow visualization was conducted by many investigators [7–12] to study oscillating flow characteristics. To characterize fluid flow, some of them performed frequency analyses on their PHPs along with flow visualization, and found either dominant oscillating frequencies ranging from 0.1 to 3 Hz [8–11] or no distinguishable frequencies due to a quite random flow behavior [12]. Due to the complexity in oscillating flow observed in the PHPs, it is not easy to theoretically describe the oscillating motion in PHPs.

As an attempt to understand the complex oscillating motion in PHPs, Das et al. [13] conducted a flow visualization experiment and proposed a model to examine the experimentally-observed oscillation of a meniscus in a one liquid slug-one vapor bubble system. Even though this study lends a broad understanding on the oscillating mechanism of the one liquid slug-one vapor bubble system, a relative motion between multiple slugs/plugs in a multi-turn PHP cannot be explained from the results obtained in their study.

Several theoretical studies [14–16] were undertaken to examine oscillating flow characteristics such as oscillation frequencies and the relative motion between neighboring liquid slugs in multi-turn PHPs. Zhang and Faghri [14] numerically investigated the oscillating motion in PHPs with an arbitrary number of turns. Their numerical results showed that the phase difference between

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Nomenclature

$\mathbf{0}$	column vector of zeros [–]
A	area [m^2]
c	damping ratio [kg/s]
c_V	specific heat [J/kg·K]
D_h	hydraulic diameter [m]
d_p	thermal penetration depth, $d_p = \sqrt{\alpha_v/\omega}$ [m]
det	determinant [–]
F	force [N]
F_0	force magnitude [N]
f	oscillation frequency [Hz]
g	gravitational acceleration [m/s^2]
i	specific enthalpy [J/kg]
I	electric current [A]
$\mathbf{K_v}$	vapor spring constant matrix [N/m]
k	spring constant [N/m]
k_B	Boltzmann constant [J/K]
L	length [m]
$\mathbf{M_l}$	liquid mass matrix [kg]
m	mass [kg]
m''	mass flux [kg/m^2·s]
$\dot{m}$	mass transfer rate [kg/s]
m_m	mass of a molecule [kg]
P	pressure [Pa]
Q	heat transfer rate [W]
Q_{in}	input power [W]
q''	heat flux [W/m^2]
R_{th}	thermal resistance [K/W]
R_v	gas constant [J/kg·K]
T	temperature [°C]
t	time [sec]
V	electric voltage [V]
X	oscillation amplitude [m]
$\mathbf{x_l}$	displacement vector of liquid masses [m]
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	location of the meniscus [m]
Z	compressibility factor [–]

Greek symbols

α_v	thermal diffusivity of the working fluid in the vapor phase [m^2/s]
δ_F	liquid film thickness [m]
η_e	evaporation coefficient [–]
η_c	condensation coefficient [–]
θ	angle [°]
λ	thermal conductivity [W/m·K]
μ	viscosity [Pa·s]
ρ	density [kg/m^3]
τ	oscillation period [sec]
ω	angular frequency [rad/s]

Subscripts

c	condenser
$cond$	condensation
e	evaporator
$evap$	evaporation
g	gravity
h	heat transfer
j	meniscus number
I	liquid-vapor interface
l	liquid phase or liquid slug
n	liquid slug/vapor plug number
sat	saturation
v	vapor phase or vapor plug

neighboring liquid slugs was approximately π regardless of the number of turns. Daimaru et al. [15] performed a numerical simulation of an eight-turn PHP and reported that the phase difference between neighboring vapor plugs was around $2\pi/8$. Peng et al. [16] presented a nonlinear thermo-mechanical finite-element model for multi-turn PHPs. To find the natural frequencies of their PHPs, they performed a modal analysis by regarding a vapor plug as a spring. Although a number of theoretical analyses have been performed by many investigators, most of the numerical results for oscillating flow have not been directly compared with experimentally-observed oscillating motion.

The purpose of the present study is to experimentally and theoretically investigate the characteristics of oscillating motion in an MPHP with multi-turns. A meandering rectangular micro-channel with a hydraulic diameter of 667 μm is engraved on a silicon wafer to form a five-turn closed-loop using a micro-electromechanical fabrication technique. Oscillating flow in the MPHP is visualized through a glass cover using a high-speed camera in conjunction with temperature measurement. A vapor spring-liquid mass model is adopted to present a closed-form expression for the experimentally-observed oscillating motion. To quantitatively explain the oscillating mechanism by the vapor spring, a link between the spring motion of the vapor plug and heat transfer to the vapor plug is sought. Finally, a semi-analytic model for a vapor spring constant, which is a key element for relating the heat transfer rate to the spring motion, is proposed and validated with the experimental results.

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 having 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. As shown in Fig. 1 [17], the overall dimensions of the MPHP were $50 \times 18.5 \times 1.7$ mm^3. The length of the condenser, adiabatic, and evaporator sections were 30%, 50%, and 20% of the MPHP, respectively, and detailed information on sizes is presented in Fig. 1(b). Two holes were fabricated on the MPHP for evacuation and charging of the working fluid, which was ethanol, in the MPHP. The MPHP was evacuated to less than 10^{-3} Torr by using a combination of a turbine pump and a rotary pump. After the degassing process, the working fluid was charged into the evacuated MPHP until the filling ratio (defined as the volume fraction of the working fluid in liquid phase at room temperature) reached 55%.

2.2. Experimental setup

A schematic diagram of the experimental apparatus is shown in Fig. 2 [17]. To minimize heat loss from the MPHP to the environ-