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Effects of the number of turns and the inclination angle on the operating limit of micro pulsating heat pipes

Jungseok Lee, Younghwan Joo, Sung Jin Kim *

Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Daejeon 305-701, Republic of Korea

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ABSTRACT

The effects of the number of turns and the inclination angle on the operating limit of micro pulsating heat pipes (MPHPs) are investigated through a series of experiments. Square channels with 5, 10, 15, and 20 turns are engraved onto a silicon wafer to form a serpentine closed loop. A glass wafer is anodically bonded to the silicon wafer for flow visualization, and FC-72 is used as the working fluid. Experimental results show that the dependence of the maximum allowable heat flux on the inclination angle becomes weaker as the number of turns increases, and it is negligible when the number of turns is 20. For this orientation-independent case with a large number of turns (20 turns or more), a new film-formation model of the operating limit is proposed: it is postulated that the MPHPs reach the operating limit when the average rate of film formation caused by the motion of the liquid slugs is smaller than the evaporation rate in the evaporator section. This postulate is experimentally confirmed through comparison between the two rates. By combining the film-formation model with the existing falling-film model, a correlation for predicting the maximum allowable heat flux covering a complete range of the number of turns is developed.

1. Introduction

In recent years, advances in the performance of electronic devices combined with the decrease in their size have led to a rapid rise in heat flux. For reliable operation of flexible and thin electronic devices currently under development, pulsating heat pipes (PHPs) are considered a promising cooling solution due to their simple design and high thermal performance [1–4]. A PHP is made up of a small and serpentine channel filled with a working fluid. When the working fluid starts an oscillating motion, PHPs have an operating range, in which they show a stable thermal performance [5–7]. When the input heat flux increases beyond its maximum allowable value, the thermal performance deteriorates significantly due to the operating limit [8–12]. Hence, it is necessary to predict when this operating limit occurs because the operating limit results in the failure of electronic devices.

Since PHPs are used in various orientations, several researchers have studied the operating limit of PHPs at various inclination angles [13–15]. Ji et al. [13] performed experiments using copper-based tubular PHPs for various working fluids, filling ratios, condenser temperatures, and inclination angles. They found that the maximum input power just before the operating limit of the PHPs with 6 turns decreased as the inclination angle changed from a vertical orientation (90°) to a horizontal orientation (0°). Qu et al. [14] observed that the maximum allowable heat flux of their silicon-based flat-plate PHPs with 5 and 7 turns had the orientation-dependent characteristics. On the other hand, Yang et al. [15] reported that their copper-based tubular PHPs with 20 turns showed almost the same maximum allowable heat flux both in horizontal and vertical orientations. From these previous studies, it can be inferred that the operating limit of PHPs depends not only on the inclination angle but also on the number of turns.

In our previous work [16], the falling-film model was proposed to predict the operating limit of micro pulsating heat pipes (MPHPs). According to this model, MPHPs reach their operating limit if the liquid supply rate by the falling film due to the gravitational force is smaller than the evaporation rate. This model was experimentally validated using MPHPs with 5 turns in a vertical orientation. However, since the falling-film model implies that the operating limit of MPHPs depends on the gravitational force, this model cannot be applied to MPHPs with many turns or in a horizontal orientation, which are not affected by the gravitational force. Therefore, it is necessary to develop a new model for the operating limit of MPHPs that are not dependent on the gravita-

* Corresponding author.
E-mail address: sungjinkim@kaist.ac.kr (S.J. Kim).

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Nomenclature

a	acceleration of the meniscus [m/s^2]
A	area [m^2]
C	empirical constant [–]
D_h	hydraulic diameter [m]
f	frequency of liquid-film formation [Hz]
g	gravitational acceleration [m/s^2]
h_{lv}	latent heat [J/kg]
L	length [m]
$\dot{m}_e$	evaporation rate [kg/s]
n_t	number of turns [–]
Q	heat rate [W]
q''	heat flux [W/m^2]
q''_{max}	maximum allowable heat flux [W/m^2]
$(q''_{max})^*$	dimensionless maximum allowable heat flux [–]
R_{th}	thermal resistance [K/W]
r	radius [m]
t	time [sec]
$\bar{T}$	average temperature [°C]
u	velocity of the meniscus [m/s]
w	width of the MPHPs [m]

Greek symbols

Γ	film flow rate [kg/s]
δ	liquid film thickness [m]
θ	cross-sectional angle [°]
μ	viscosity [Pa·s]
ρ	density [kg/m^3]
ϕ	inclination angle [°]

Subscripts

c	condenser
e	evaporator or evaporation
fall	falling-film model
form	film-formation model
in	total input
l	liquid phase
v	vapor phase

tional force in order to predict the operating limit of MPHPs for various numbers of turns and inclination angles.

The purpose of the present study is to investigate the operating limit of MPHPs for various numbers of turns and inclination angles. For this purpose, a serpentine square channel is engraved onto a silicon wafer to fabricate MPHPs with 5, 10, 15, and 20 turns. Experimental investigations into the effects of the number of turns and the inclination angle on the flow and heat transfer characteristics are carried out by the thermometry and the flow visualization using high-speed photography. From the experimental observations, a model that considers the operating limit of MPHPs unaffected by gravitational force is suggested and validated. Using the results obtained from the model, a correlation for the maximum allowable heat flux in terms of the number of turns and the inclination angle is developed.

2. Experiments

2.1. MPHP specimens for experiments

Square-channel MPHPs whose hydraulic diameter is 480 μm were fabricated using the same way as our previous work [16]. Fluorinert liquid FC-72 was used as a working fluid. A filling ratio that means the ratio of the filled volume of liquid to the total volume of the entire channel was fixed at 50%. Fig. 1 presents the schematic diagram and dimensions of the MPHPs. The widths (w) of the MPHPs with 5, 10, 15, and 20 turns were 16, 24.9, 34.7, and 44.5 mm, respectively. The lengths of the evaporator, adiabatic, and condenser sections were 10, 25, and 15 mm, respectively. The temperature measurement points were centered on each section, as shown in Fig. 1. Experimental parameters are summarized in Table 1.

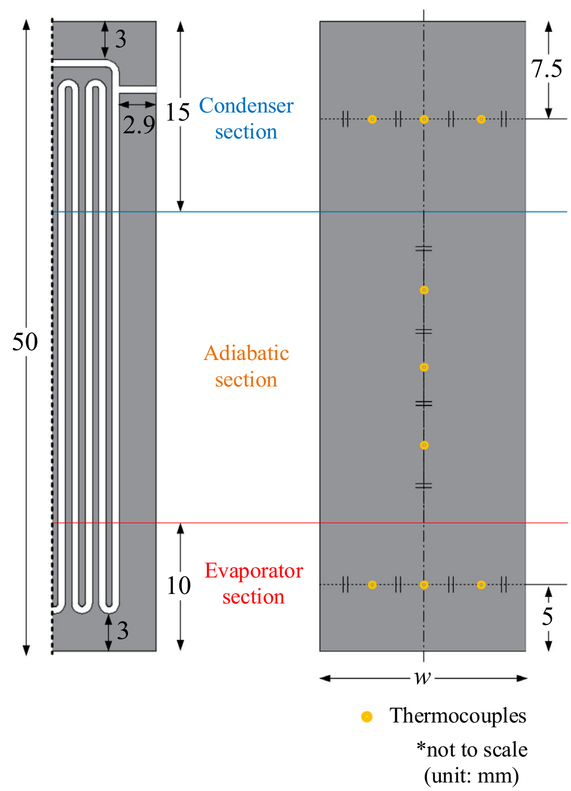

Fig. 1. Schematic and dimensions of the MPHP.

2.2. Experimental setup

Fig. 2 depicts the experimental setup for estimating the thermal performance of the MPHPs. Details were described in our previous work [16]. Experiments were performed in a vacuum chamber in order to minimize the heat loss from an MPHP to the environment. The inclination angle was varied from a vertical orientation (90°) to a horizontal orientation (0°) using a step motor. The input power into the heater was increased stepwise by 0.5 or 2 W until the MPHPs reached their operating limit. Flow visualization was performed using a high-speed camera.

The thermal resistance obtained from the following equation represented the thermal performance of the MPHP.

$$R_{th} = \frac{\overline{T_e} - \overline{T_c}}{Q_{in}} \tag{1}$$

where $\overline{T_e}$, $\overline{T_c}$, and Q_{in} are the average temperature of the evaporator section, the average temperature of the condenser section, and the