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Operational characteristics of pulsating heat pipes with a dual-diameter tube

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ABSTRACT

A series of experiments was performed to investigate the effect of a dual-diameter tube on the flow and heat transfer characteristics of single-turn pulsating heat pipes (PHPs). Various types of PHPs were made of glass capillary tubes with various inner diameters. Using thermometry and high-speed photography, experiments to quantitatively observe operational characteristics of the PHPs were performed with varying input power and inclination angle. The results show that circulating flow promoted by a dual-diameter tube reduces thermal resistance of the PHP by as much as 45%. Based on experimental observations, a simplified model was developed to predict thermal performance of PHPs with circulating flow, and the results based on the model matched well with experimental data to within the error of 15%. The data calculated by the proposed model show that there is an optimum range of diameter difference where the thermal performance enhancement is maximized. The optimal range of the dimensionless diameter difference is found to be $0.25 < \Delta D/D_{avg} < 0.4$.

1. Introduction

A heat pipe, a type of passive thermal control device, is one of the most efficient and attractive technologies for high heat flux electronic cooling. However, the increase in performance and the miniaturization of electronic system results in new requirements that cannot be satisfied by conventional heat pipes [1,2]. Especially, the flexibility in the shape of conventional heat pipes has been the chief obstacle for effective cooling of various shaped electronics because wick structure is inappropriate to shape deformation. Thus, evolution in the design of the heat pipe has accelerated in the past decade, and new types of heat pipes, such as capillary pumped loops (CPLs), loop heat pipes (LHPs), and pulsating heat pipes (PHPs), were introduced to overcome the inherent limitations of conventional heat pipes [3]. Although CPLs and LHPs possess some advantages over conventional heat pipes, they also have a wick structure in the evaporator. Therefore, among these heat pipes, PHPs have shown great promise for thermal management of very thin electronic devices due to their very simple structure which consists of a small and long meandering tube without any wick structure [4].

Although their structure is simple, PHPs are a complex heat transfer device whose thermal performance is governed by a strong thermo-hydrodynamic coupling [2]. A number of studies have been performed so far to understand the operational characteristics of PHPs [5]. Previous studies reported that heat transfer performance of a PHP is enhanced when a PHP has a circulating flow instead of an oscillating flow [6–8]. Therefore, the development of a PHP which has a circulating flow under a wide range of working conditions would be essential in improving the thermal performance of PHPs. Some researchers [2,6,9–11] have proposed special configurations of PHPs to promote a circulating flow in PHPs. They found that an asymmetric configuration helps to promote a circulating flow and enhance heat transfer performance. Among these, Liu et al. [10] reported that an asymmetric PHP with a dual-diameter tube of inner diameters of 2 and 1.6 mm, respectively, has lower thermal resistance than a conventional PHP with a uniform-inner diameter tube of 1.6 mm. Even though their experiments provided some clue to thermal performance enhancement of the asymmetric PHP, a question arises as to what should be a proper difference in tube diameters for which a circulating flow is guaranteed and the thermal performance of a PHP is maximized. If the difference between the two tube diameters is small, it makes little difference to operational characteristics of a PHP. On the other hand, too large a diameter difference could lead to an adverse effect on the performance due to large imbalance in driving forces and flow resistances. To the authors' knowledge, however, no experimental study has been performed to answer this question for an asymmetric PHP.

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Nomenclature

A_c	cross sectional area [m^2]
A_s	surface area [m^2]
Bo	boiling number [-]
c_p	specific heat capacity [J/kg K]
Co	convection number [-]
D	diameter [m]
D_{avg}	average diameter [m]
F_c	thermocapillary force per unit volume [N/m^3]
F_{tc}	thermocapillary force [N]
F_f	frictional force [N]
F_g	gravitational force [N]
F_{sat}	force due to saturation pressure difference [N]
f_{TP}	friction factor [-]
G	mass flux [kg/s m^2]
g	gravitational acceleration [m/s^2]
H	enthalpy [J/kg K]
h	heat transfer coefficient [W/m^2 K]
H_{fg}	latent heat [J/kg]
h_{lo}	single-phase heat transfer coefficient [W/m^2 K]
I	electric current [A]
j	fluid velocity [m/s]
k	thermal conductivity [W/m K]
L	length [m]
$\dot{m}$	mass flow rate [kg/s]
P	pressure [N/m^2]
Pr	Prandtl number [-]
p_w	perimeter [m]
Q_{in}	supplied input power [W]
Q_{out}	power removed in condenser [W]
Re	Reynolds number [-]
q''	heat flux [W/m^2]
R_{th}	thermal resistance [K/W]
r_{out}	outer radius [m]
r_{in}	inner radius [m]
T	inner wall temperature [°C]
$\overline{T}$	average inner wall temperature [°C]
T_{out}	outer wall temperature [°C]
T_f	temperature of working fluid [°C]
T_w	temperature of chilled water [°C]
t	time [sec]
V	electric voltage [V]
x	vapor quality [-]
z	distance [m]

Greek symbols

ρ	density [kg/m^3]
θ	inclination angle [°]
τ_w	wall shear stress [N/m^2]
v	specific volume [m^3/kg]
μ	viscosity [Pa s]
σ	surface tension [N/m]

Subscripts

c	condenser
e	evaporator
f	working fluid
glass	glass
in	inlet
L	left tube
l	liquid phase
lat	latent heat transfer
out	outlet
R	right tube
sen	sensible heat transfer
TP	two-phase
tc	thermocapillary
v	vapor phase
w	chilled water

The purpose of this study is to determine the proper difference in tube diameters (or the proper dimensionless diameter difference defined as the ratio of the diameter difference to the average tube diameter) for which the thermal performance enhancement is maximized by effectively promoting a circulating flow. Experimental and theoretical investigations into the effect of a dual-diameter tube on operational characteristics of PHPs were performed. To understand fundamental operating principles, flow visualization with high-speed photography was conducted using various types of single-turn PHPs made of glass capillary tubes. A series of experiments was quantitatively performed with varying input power and inclination angle: flow and heat transfer characteristics of PHPs with a dual-diameter tube were compared with those of PHPs with a uniform-diameter tube. Based on experimental observations, a theoretical model was also proposed to predict the operational characteristics of PHPs with a circulating flow and to provide guidelines for the design of PHPs with a dual-diameter tube which have improved thermal performance. Results from the proposed model were used to find the optimal dimensionless difference for which the thermal performance enhancement is maximized.

2. Experiments

2.1. Experimental apparatus

Fig. 1 shows the schematic diagram of the experimental setup. Single-turn PHPs were made of two interconnected borosilicate glass tubes (DURAN, Boroα3.3) forming a closed loop. As listed in Table 1, six types of PHPs were fabricated; three of them were symmetric PHPs with a uniform inner diameter tube (PHPs Nos. 1, 2, and 3), and the other three were asymmetric PHPs with a dual-diameter tube (PHPs Nos. 4, 5, and 6). The latter had two adjacent tubes of different inner diameters with a gradually changing inner diameter. Once fabricated, the PHP was degased and charged with a tightly controlled amount of working fluid. The degassing processes are identical to those explained in Ref. [4]. The purified and degased working fluid was charged into the PHP as much as needed. The working fluid in the PHP was frozen, and the PHP was evacuated to about 10^{-2} Torr using the rotary pump (W2V20, WOOSUNG AUTOMA CO., Ltd.). Finally, the PHP was sealed off by oxygen propane torch. The filling ratio (defined as the volume fraction occupied by the liquid in the channel at room temperature) was fixed at 50%. The filling ratio was confirmed by calculating the number of pixels from the charged PHP image.

The experimental apparatus used to evaluate the thermal performance of a glass capillary PHP consisted of a PHP, a chrome wire heater, a DC power supply, a condenser made of copper block, a bath circulator (cooling chamber), K-type thermocouples, a data acquisition system (DAQ), and a computer. A high-speed camera (M320S, Phantom) was used to visualize the flow behaviors inside the PHPs. The heater, made of Nichrome wire with diameter of 0.75 mm, was used to create a uniform heat flux condition in the evaporator section and was connected to a DC power supply (N5767A, Agilent technologies) for thermal performance evaluation of the PHPs. To visualize the internal flow of the PHPs,