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Thermal performance characteristics of a pulsating heat pipe at various nonuniform heating conditions

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ABSTRACT

A pulsating heat pipe (PHP) is an excellent cooling device based on the phase change of a working fluid. However, the performance of the PHP can be degraded by nonuniform heating conditions in the evaporator section. The objective of this study is to investigate the thermal performance characteristics of a PHP at various nonuniform heating conditions. The thermal performance of the PHP is measured by varying the dimensionless heat difference from 0 to 0.3, heat input from 30 to 100 W, and filling ratio from 50% to 70%. As a result, the optimal filling ratios for the best PHP performance and reliability are determined to be 50%, 60%, and 70%, at the dimensionless heat differences of 0, 0.2, and 0.3, respectively. In addition, the thermal resistance and evaporator temperature difference of the PHP increase with an increase in the dimensionless heat difference owing to the decreased driving force. Finally, contour maps for the effective thermal conductivity are proposed to provide design guides of PHPs.

1. Introduction

Thermal management in electronic equipment, such as microchips and battery cells, is an important issue owing to the increased power density of such equipment. Therefore, effective cooling methods that dissipate heat generated in a compact space have been investigated extensively [1–5]. A pulsating heat pipe (PHP) elicits a high heat transfer performance as a cooling device based on phase changes of a working fluid. The major operating factor in the PHP is the pressure difference during the expansion and disappearance of bubbles in multiple channels. This force causes liquid slugs and vapor plugs to oscillate or circulate, which in turn allow transfer of heat from hot to cold regions. The thermal performance of the PHP is affected by various geometrical and operating parameters, such as channel geometry, working fluid, and operating conditions [6–9].

In general, the thermal resistance decreases as the heat flux increases owing to the increase in the fluid oscillating motion with increased pressure fluctuations [10,11]. Several studies [12–16] have been conducted to investigate the effects of the heat flux on the thermal performance of PHPs using various geometric parameters, such as the internal diameter, cross-sectional shape, number of turns, and heat transfer length. Moreover, Kim et al. [17] investigated the performance of a PHP considering temperature fluctuations in the heating and cooling sections. As the amplitude and frequency of the periodic fluctuation in the wall temperature increased, the frequency of the liquid slug oscillation decreased. Xian et al. [18] investigated the heat transfer characteristics of a PHP with pulse heating. Overall, the thermal performance of a PHP varies with respect to the heat flux and nonuniformity of the heat input.

An optimal filling ratio in a PHP has been studied to achieve stable operation at various operating conditions. The filling ratio (α) is defined as the ratio of the volume of the working fluid in the liquid state to the total volume of the PHP. For low filling ratios, dry-out occurs easily owing to a decrease in the proportion of liquid. For high filling ratios, the fluid oscillation motion and pressure fluctuation decrease owing to a decrease in the proportion of vapor [19,20]. Qu et al. [13] investigated the heat transfer characteristics of silicon-based micro PHPs by varying the filling ratio and working fluid in various operating conditions. Liu et al. [21] analyzed the start-up performance of a PHP with various working fluids. Moreover, the thermal performance of PHPs was investigated by using mixtures of working fluids at various filling ratios, mixing ratios, and heat inputs [22–24]. Overall, the optimal filling ratio that will yield the maximum performance at various operating conditions needs to be identified.

As stated previously, many studies on PHPs have been conducted at various heat inputs where the heat is uniformly distributed in the evaporator section. However, in actual applications, the heat is not generated uniformly. Therefore, it is

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Nomenclature

A_c	cross-sectional area (mm^2)
f	maximum thermal performance ratio
k_{eff}	effective thermal conductivity (kW m^{-1} °C^{-1})
L	length (mm)
L_{eff}	effective heat transfer length (mm)
P	pressure (kPa)
Q_{total}	total heat input (W)
Q_1	high heat input (W)
Q_2	low heat input (W)
R	thermal resistance (°C W^{-1})
T	temperature (°C)

Greek symbols

α	filling ratio
ϕ	dimensionless heat difference

Subscripts

a	adiabatic
c	condenser
e	evaporator
non-uni	nonuniform heat
uni	uniform heat

required that the effects of nonuniformly distributed heating conditions on the performance of PHPs are investigated owing to the performance degradation at increased thermal resistance or increased local temperature. Moreover, the effects of heat nonuniformity on the performance of PHPs can vary according to the filling ratio. However, the effects of the filling ratio on the performance of PHPs at nonuniform heating conditions have been rarely investigated in the literature.

For the optimal design of PHPs under actual operating conditions, it is essential to analyze the performance of PHPs by varying the filling ratio in the evaporator section at nonuniform heating conditions. The objective of this study is to investigate the heat transfer characteristics of a PHP at various filling ratios under nonuniform heating conditions. In this study, the flow characteristics and thermal performance of the PHP were measured by varying the heat input, nonuniformity of heat, and filling ratio. The flow characteristics in the PHP were analyzed by measuring the temperature, pressure, and pressure frequency using the fast Fourier transform (FFT). Moreover, the effects of the nonuniformity of the heat and filling ratio on the thermal resistance and evaporator temperature difference between two heat sources were analyzed based on the measured data at various heat inputs. Finally, contour maps were proposed to provide design guides of PHPs in terms of the nonuniformity of the heat and filling ratio.

2. Experimental setup and test procedure

2.1. Experimental setup

Fig. 1 shows a schematic of the experimental setup. The evaporator section was heated with cartridge heaters inserted in aluminum blocks. The thermal loads were controlled by DC power supplies. The condenser section was cooled with water flowing through channels in the aluminum block. The water was circulated by a bath circulator, and the inlet temperature was maintained at 25 °C. The exterior parts of the heater and cooler were insulated with polyurethane foam to minimize heat loss.

Fig. 2 shows a schematic of the PHP used in this study. The PHP was made of a copper tube with an internal diameter of 1.5 mm. The height of the PHP was 270 mm and there were eight turns. The lengths of the evaporator, adiabatic, and condenser sections were 30 mm, 60 mm, and 90 mm, respectively. The heaters on the evaporator were installed on the left and right sides of the PHP to provide different heat inputs.

T-type thermocouples were used to measure the temperature at the evaporator and condenser sections, which were also attached to the outside of the PHP to observe the internal temperature indirectly. Pressure transducers were installed at the adiabatic section to measure the pressure of the working fluid in the PHP. The accuracies of the T-type thermocouple and the pressure transducer were ±0.2 K and ±0.1% of the full scale, respectively. The power input to the evaporator section was measured by a power meter with an accuracy of ±0.01%.

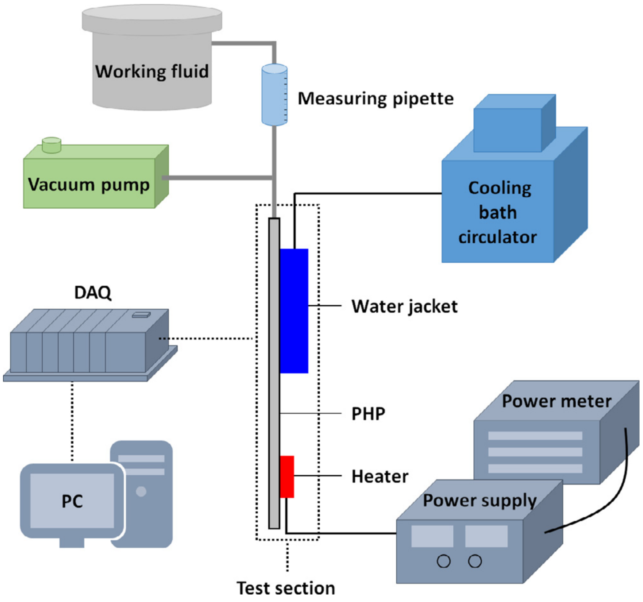

Fig. 1. Schematic of the experimental setup.

2.2. Test procedure and test conditions

Prior to injecting the working fluid, the PHP was evacuated up to 1 Pa using a vacuum pump. Moreover, noncondensable gases in the working fluid were removed by the degassing process. During the degassing process, the working fluid in the vacuum chamber was heated and then cooled several times to obtain a purified fluid. After the degassing process, the working fluid was charged into the PHP precisely using a mass pipette to obtain the target filling ratio.

After reaching the steady state of the test condition, the temperature data were collected using a data acquisition unit within a time interval of 1 s, while the pressure data were collected within a time interval of 0.05 s. Each data point presented in this study shows the average value of recordings spanning 10 min intervals under steady state. Based on the experiments, the heat loss, which was calculated by comparing the heating load of the heaters in the evaporator and the cooling load of the bath circulator in the condenser, was less than ±3%.

The tests were conducted along the vertical orientation of the PHP. The evaporator section was located at the bottom (referred to as the bottom heating mode) and the condenser section was