Heat transfer characteristics of flat plate pulsating heat pipe using self-rewetting fluids

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Abstract

The heat-transfer performance of a pulsating heat pipe (PHP) was evaluated. The aluminum-plate PHP consists of 24 parallel 2×2 mm^2 square channels. Water and self-rewetting fluids were used as the working fluids. The self-rewetting fluid is a dilute aqueous solution of alcohols (such as butanol and pentanol) that consist of a large number of carbon atoms. These solutions can be considered self-rewetting fluids, owing to the non-linear temperature dependence of the corresponding surface tension and the ability to spontaneously wet a hotter region. The experimental results indicated that, compared with the water, the self-rewetting fluid resulted in a significantly better heat-transfer performance; this resulted from a decrease in the temperature difference between the heating and cooling sections and the thermal resistance. Moreover, flow visualization of the heating section revealed that the boiling phenomena of the self-rewetting fluid are more pronounced than those associated with the water. In the case of the self-rewetting fluid, the temperature and pressure fluctuations were both stable and continuous, owing to the occurrence of these phenomena.

Keywords: Flow visualization, Heat transfer performance evaluation, Pulsating heat pipe, Self-rewetting fluids

1. INTRODUCTION

In recent years, the demand for satellites and various types of spacecraft has increased and hence, development of the required high-performance and high-density internal components is ongoing. The heat flux of electronics is also increasing rapidly and therefore, the demand for more efficient heat-control devices, than those currently available, has also increased. Moreover, a low-weight and small (owing to size limitations stemming from the miniaturization of electronics) thermal-control device that uses minimal power, is highly desirable. Pulsating heat pipes have therefore attracted attention as the next generation of thermal-control devices that meet these requirements.

The pulsating heat pipe (PHP) is a new type of efficient heat-transfer device, which was introduced in the mid-1990s by Akachi [1]. The basic structure of a typical PHP consists of a meandering capillary tube that is partially filled with a working fluid, as shown in Figure 1. The PHP transports heat via pulsation of the working fluids in the flow channel; these pulsations result from pressure fluctuations associated with evaporation and condensation. In addition, the high heat-transfer performance, owing to sensible and latent heat, constitutes a unique feature that renders PHP superior to convectional heat pipes. The PHP is also well-suited for miniaturization, owing to its simple no-pump structure, and can be operated under low gravity. Owing to these attributes, the PHP constitutes a promising means of solving the internal heat-generation problems associated with spacecraft.

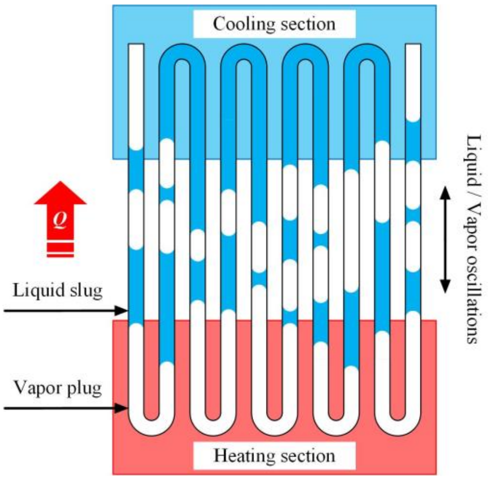

Figure 1 Structure of a PHP.

Several studies, via experiments, of the heat-transfer characteristics of PHP have revealed the parameters (geometry, filling ratio, inclination angle, working fluid, etc.) that affect the performance of PHP. For example, Fumoto et al. [2] have evaluated the performance of the PHP, when self-rewetting fluids were used as the working fluid sealed inside the PHP. The self-rewetting fluids are alcohol dilute aqueous solutions (such as butanol and pentanol)

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that consist of four or more carbon atoms. According to these authors, use of the self-rewetting fluids yields a higher heat-transport capability of the PHP compared to that resulting from the use of water. Yanxin et al. [3] determined, via experiments, the strengthening effect of self-rewetting fluids on this heat-transport capability. They found that the self-rewetting fluid, as the working fluid of the PHP, leads to a decrease in the thermal resistance and extends the effective operating range of the PHP. The aforementioned results confirm the heat transfer performance-enhancement effect of self-rewetting fluids. However, the mechanism governing this mechanism remains unclear.

Therefore, the main purpose of this study is to clarify the performance-enhancement mechanism by using self-rewetting fluids in a flat-plate aluminum PHP.

2. EXPERIMENTS

2.1 Experimental apparatus

Figure 2 shows the experimental apparatus, which consists of a PHP, an electrical power input source, as well as a water-cooling system, vacuum device, working fluid supply unit, temperature and pressure data logger, high-speed camera system, and a PC. As Figure 3 shows, the 236×119×3 mm^3 aluminum-plate PHP test sections consist of 24 parallel square channels that form a meandering open loop (cross-section: 2×2 mm^2, length per tube: 180 mm). A polycarbonate plate with a thin transparent silicon sheet was used to cover the top of the PHP, to allow visualization of the internal flow phenomena, from above. The heating section consisted of two cartridge heaters (ϕ10×60 mm) embedded in an aluminum heating block (75×40×20 mm^3), and the power supplied to the heaters was varied from 0–320 W. The aluminum cooling block (75×40×20 mm^3) was cooled by a water jacket connected to a water-circulation system. The cooling and heating blocks were attached, in separate locations, to the back face of the PHP. The temperature of the PHP was measured by nine K-type thermocouples (with a wire diameter of 127 μm) that were attached to the back face of the PHP. Three thermocouples, each, were attached to the cooling section (T_1-T_3), symmetrically placed in the heating section (T_7-T_9), and placed in the adiabatic section along the center line (T_4-T_6), respectively. In addition, in order to measure the pressure inside the PHP, pressure sensors were integrated into the polycarbonate plate in both the heating and cooling sections (see Figure 4). Two types of working fluids, namely, deionized water, and a self-rewetting fluid, were used in the present study. The self-rewetting fluid was prepared by adding 1-butanol to deionized water, thereby yielding an aqueous solution of specified mass concentration.

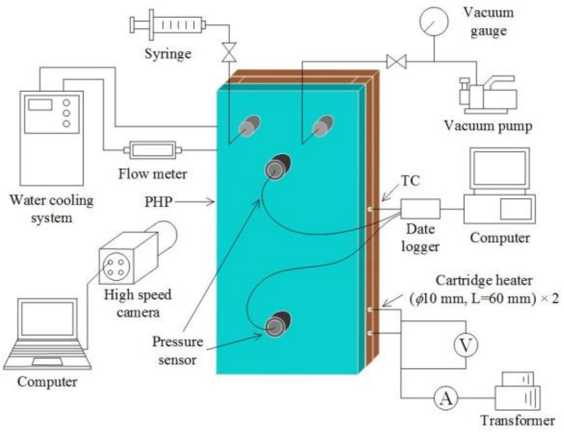
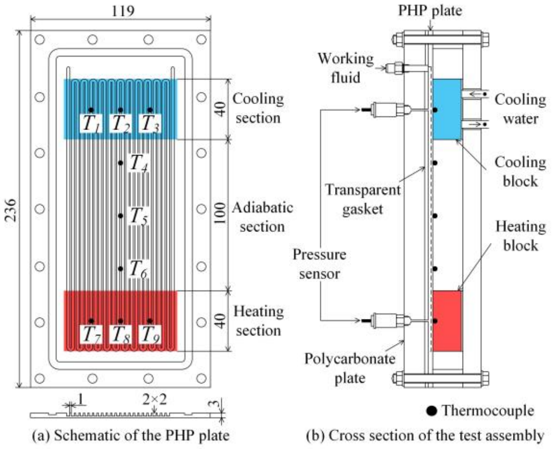


Figure 2 Schematic of the experimental apparatus.



(a) Schematic of the PHP plate (b) Cross section of the test assembly

Figure 3 Components of the PHP.

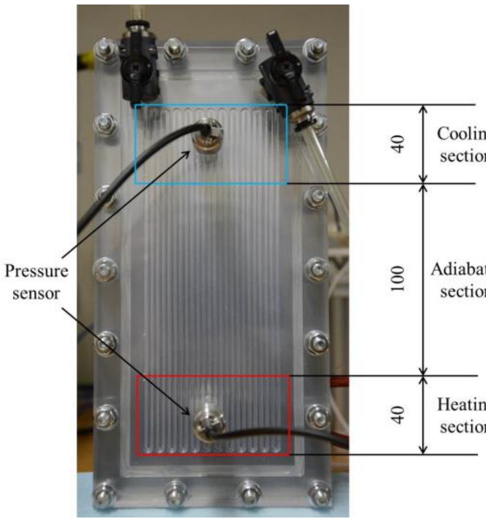


Figure 4 Photo of the PHP.

2.2 Experimental procedure

To charge the PHP to a specified filling ratio (FR), the heat pipe was vacuumed to a pressure of 3 kPa, by using a gauge. A specified amount of the working fluid was then injected into the PHP, by using a syringe. The filling ratio was confirmed by using an electronic balance to measure the mass of the syringe before and after the filling operation. The power supplied to the cartridge heater block was adjusted after the back face of the PHP reached a steady-state temperature condition. When a heating-section temperature of 120 ºC was reached, the experiment was terminated by switching off the heater. The experiment was performed under the following conditions: constant temperature of 20 °C, cooling water circulation, FR of 50 vol.%, working fluids with concentrations of 1, 3, and 7.15 wt.% of a butanol aqueous solution, and a vertical bottom heat mode.

2.3 Data reduction

The thermal resistance (R) and the temperature difference between the heating and cooling sections (ΔT) constitute important parameters that describe the heat-transfer performance of the PHP. R and ΔT are given as:

$$R = \Delta T / Q \tag{1}$$

$$\Delta T = T_{h,ave} - T_{c,ave} \tag{2}$$

Where Q, $T_{h,\,ave}$, and $T_{c,\,ave}$ are the heat input power to the PHP, and the average temperature of the heating and cooling sections in the steady state, respectively

3. RESULTS AND DISCUSSION

3.1 Self-rewetting fluid

In this study, a butanol aqueous solution is used as the self-rewetting fluid; the thermo-physical properties of the working fluids used in the experiments are listed in Table 1. Previous studies have shown that, with increasing temperature, the surface tension behavior of self-rewetting fluids differs from that of ordinary pure fluids. Figure 5 shows the surface tension of an ordinary pure material and a self-rewetting fluid [4, 5], as a function of the temperature. The surface tension of the ordinary pure fluid (e.g., water and butanol) decreases linearly with increasing temperature. In contrast, the surface tension of the self-rewetting fluid (e.g., butanol aqueous solution) decreases gradually with increasing temperature, reaching a minimum at ~60 °C, and gradually increases thereafter. Therefore, in the case of a self-rewetting fluid on a heated surface, liquid-vapor interfaces and temperature gradients lead to surface tension-driven convection, as shown in Figure 6. An enhanced heat-transfer performance, owing to this convection, is therefore expected; this convection should also prevent dry-out of the heated surface [6, 7].

Table 1 Properties of working fluids.

	Working fluid (at 20 ºC, 1 atm)	
	Water	Butanol
Molar mass [g/mol]	18.02	74.1
Density [g/cm^3]	0.998	0.81
Boiling point [ºC]	100	117.65
Latent heat [MJ/kg]	2.26	0.58
Surface tension [mN/m]	71.7	24.57
Solubility in water [g/mL]	—	7.15

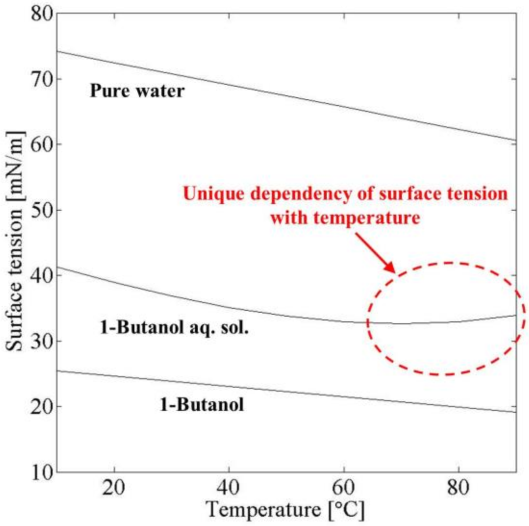


Figure 5 Temperature-dependence of the surface tension.

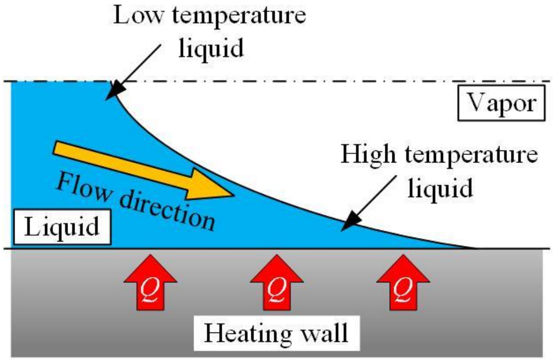


Figure 6 Surface tension-driven convection.

3.2 Heat transfer performance

Figure 7 shows the dependence of the thermal resistance on the heating power, in the case of the bottom heat mode and FR=50 vol.%. As the figure shows, the resistance decreases with increasing heat input power, irrespective of the type of working fluid. Moreover, at high input power (i.e., Q>160 W), the resistance of the PHP that uses butanol aqueous solution is lower than that of the PHP, which uses water. This results from the unique surface tension effect, associated with the solution, which leads to a lower input-power-induced temperature increase of the heating section, than that resulting from the use of water. The figure also shows that the heat-transfer performance of the solutions is relatively independent of the concentration of butanol. This results from an increase in the positive gradient of surface tension, and hence surface tension-driven convection toward the heating surface, with increasing concentration of butanol. However, sensible heat transfer of the solution decreases with increasing butanol concentration. The overall heat transfer in a PHP arises mainly from the exchange of sensible heat and therefore, the performance enhancement changes only slightly (or modestly) when a certain concentration of butanol is exceeded.

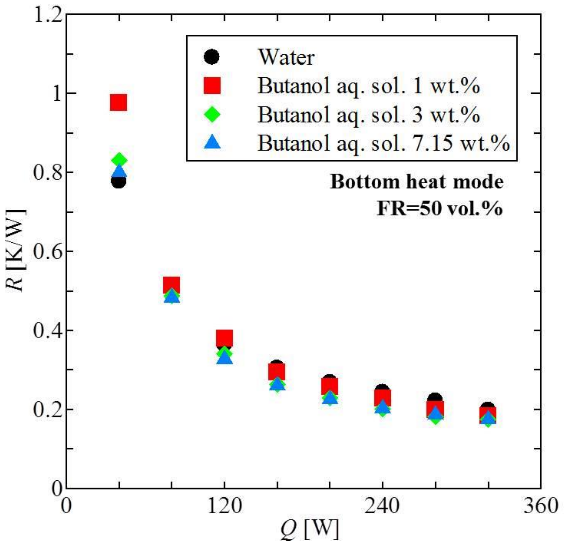
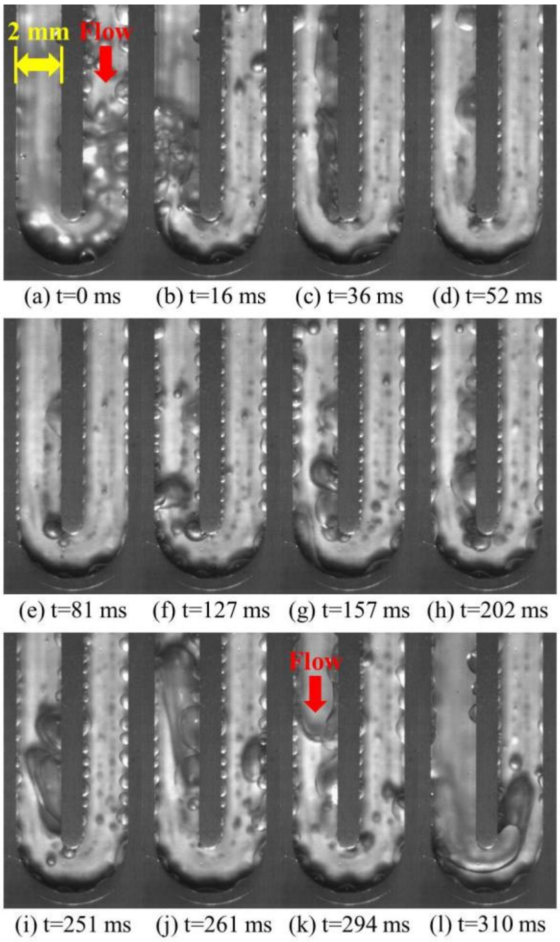


Figure 7 Thermal resistance.

3.3 Flow visualization of the heating section

Figure 8 shows a series of images that comprise a high-speed movie of the heating section. Water (a) and butanol aq. sol. 3 wt.% (b) constitute the working fluids and the filling ratio, heat input power, and orientation of the PHP are FR=50 vol.%, Q=320 W, and bottom heat mode, respectively. Flow visualization of the section revealed that the flow boiling phenomena (of the section) consist of four sequential steps (i–iv), namely, the: (i) occurrence of boiling bubbles, (ii) growth of the bubbles on the heated surface, (iii) coalescence of the grown bubbles, and (iv) separation of the coalesced bubbles from the heated surface, by the movement of liquid slugs or vapor plugs. In the case of the PHP that used water, growth of the bubbles on the heated surface was extremely slow, and the inflow frequency of liquid slug or vapor plug was low (see Figure 8(a)). Use of the butanol aq. sol. 3 wt.% resulted, however, in many boiling bubbles on the heated surface, and the boiling cycle was shorter than that of the water (see Figure 8(b)). These results suggest that the occurrence of boiling phenomena, on the heated surface, influences the heat transfer performance-enhancement mechanism of the PHP.

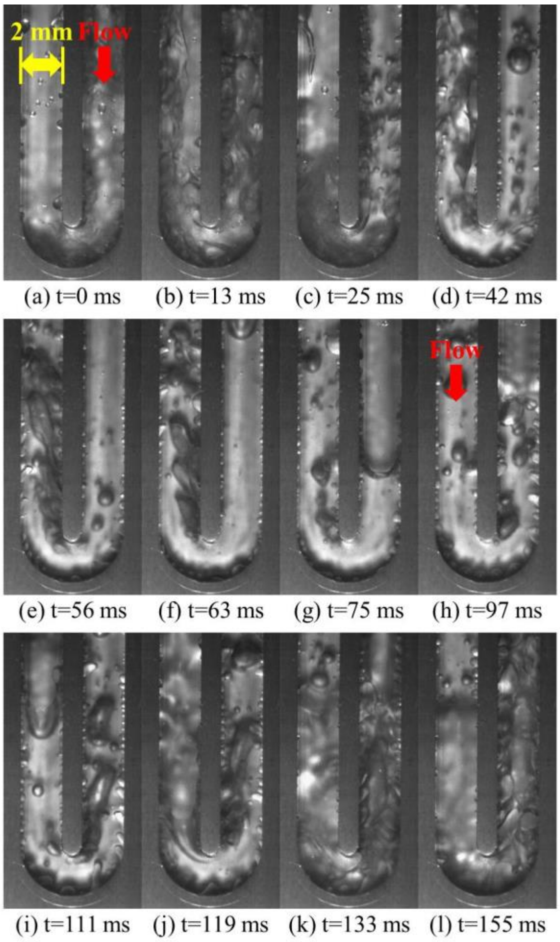


(a) t=0 ms (b) t=16 ms (c) t=36 ms (d) t=52 ms

(e) t=81 ms (f) t=127 ms (g) t=157 ms (h) t=202 ms

(i) t=251 ms (j) t=261 ms (k) t=294 ms (l) t=310 ms

(a) Water, Q=320 W

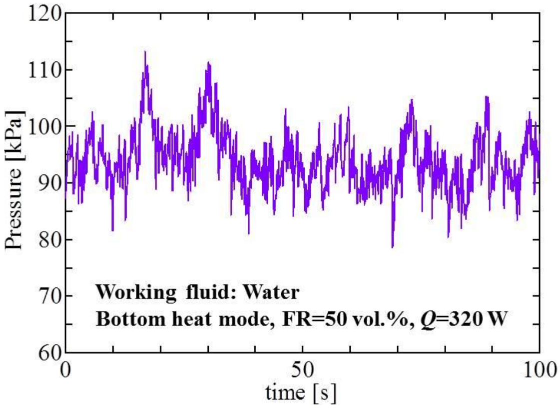


(b) Butanol aq. sol. 3 wt.%, Q=320 W

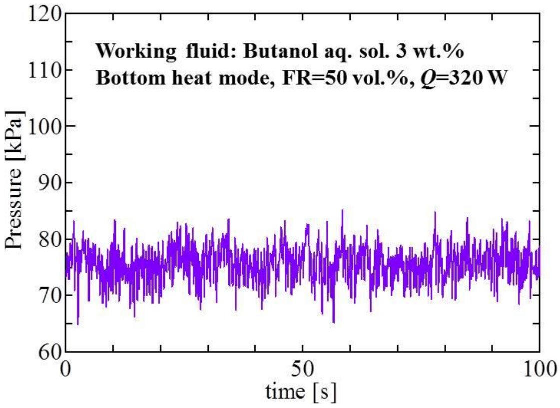
Figure 8 Flow visualization of the heating section.

3.4 Pressure history of the heating section

Figure 9 shows the pressure history of the heating section when the filling ratio, heat input power, and orientation of the PHP are FR=50 vol.%, Q=320 W, and bottom heat mode, respectively. In a PHP, the pulsating phenomenon of the working fluid is excited by the pressure fluctuation. Furthermore, the heat transfer in a PHP is dominated by the sensible heat of the liquid slug that moves between the heating and cooling sections. The behavior of pressure fluctuation is therefore directly related to the heat-transfer performance of the PHP. Large pressure fluctuations, over almost the entire timespan, occur when water is used as the working fluid; these fluctuations are accompanied by a non-periodic unstable oscillation (see Figure 9(a)). In addition, the pressure history of the water confirms the rapid pressure increase, indicating that a local dry-out occurs in the heating section. In contrast to those observed for water, the pressure oscillations are continuous in the case of butanol aq. sol. 3 wt.%, and the amplitude is constant (see Figure 9(b)). The aforementioned results indicate that the enhanced performance of self-rewetting fluids arises from the high frequency and stabilization of pressure oscillation, owing to the occurrence of the boiling phenomenon.



(a) Water, Q=320 W



(b) Butanol aq. sol. 3 wt.%, Q=320 W

Figure 9 Pressure history of the heating section.

4. CONCLUSIONS

The heat-transfer performance, flow boiling behavior, and pressure fluctuation of a PHP were investigated by performing a series of experiments. The main conclusions of this study are summarized as follows:

1. Owing to a lower thermal resistance, the PHP using butanol aqueous solutions exhibited superior heat-transfer performance, compared to its counterpart that used water as a working fluid.

2. The boiling phenomenon results from the unique surface tension effect associated with butanol aqueous solutions.

3. The enhanced heat-transfer performance, owing to the self-rewetting fluids, results mainly from an increase in the pressure frequency; this increase is induced by the boiling phenomenon that occurs in the heating section.

ACKNOWLEDGEMENT

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NOMENCLATURE

Q : Heater input power, W
T : Temperature, °C
DT : Temperature difference, °C
$T_{h, ave}$: Average heating section temperature, °C
$T_{c, ave}$: Average cooling section temperature, °C
R : Thermal resistance, K/W

Subscripts
1~9 : Thermocouple location
h : Heating section
c : Cooling section
ave : Average

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