Effect of Self-Rewetting Fluids on Pulsating Heat Pipe Thermal Performance

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ABSTRACT

Pulsating heat pipes (PHPs) have recently emerged as a possible cooling device for high heat flux electronics to replace conventional cooling devices. In this study, new experimental results were obtained for using self-rewetting fluids to enhance the heat transport of PHPs. Unlike other common liquids, the surface tension of self-rewetting fluids increases with temperature. The increase in surface tension at high temperatures causes the liquid to be drawn towards a heated surface if a dry spot appears, which improves boiling heat transfer. PHPs were constructed out of multiport extruded aluminum tubing with a square channel cross section. In experiments, heptanol was added to water at a concentration of less than 1 wt% to form the self-rewetting fluid. Several other parameters were adjusted for optimization, such as the aqueous alcohol solution concentration of the working fluid, the fluid fill ratio, and the heat pipe orientation. Using a self-rewetting fluid in PHPs was found to be highly effective in improving their heat transport capability. The PHPs delivered a better performance when oriented vertically rather than horizontally. As a working fluid, the heptanol water mixture outperformed both the butanol water mixture and pure water within the parameters of this experiment.

INTRODUCTION

Recently, as computer chips and power electronics become smaller and more densely packed, the need for more efficient cooling systems has increased. Heat pipes are very promising devices for achieving high local heat removal rates and uniform temperature on computer chips. Heat pipes that can utilize the latent heat of boiling and condensation with small temperature differences are expected to deliver large heat transport rates. Several different types of heat pipes such as a capillary pumped loop [1], counter-stream-mode oscillating-flow heat pipe [2], and pulsating heat pipe (PHP) [3]–[5] have been developed and investigated for various heat removal applications. The meandering tube PHP proposed by Akachi [6] has already been used in some micro-region applications due to its favorable operational characteristics and relatively cheap cost. The basic heat transfer mechanism in a PHP is the oscillating movement of the fluid associated with phase change phenomena. The PHP has the advantage of not needing a wick structure to transport the liquid. As shown in Figure 1, PHPs can be divided into the following two groups: (a) closed loop PHP (CLPHP) and (b) open loop PHP (OLPHP), also known as closed end PHP (CEPHP). There have been various investigations focused on enhancing the performance of PHPs. For example, Lin et al. [7] concluded that the thermal performance of silver nanofluid is slightly enhanced and its thermal resistance is slightly better than that of the base fluid. However, the nanoparticle concentration increases not only the thermal conductivity of the nanofluid but also the viscosity and possibility of particle agglomeration and settling. On the other hand, Zhang [8] and Abe et al. [9] conducted numerical and experimental investigations of heat transport enhancement using an aqueous alcohol solution in a heat pipe. The working fluid consisted of water and a small amount of alcohol, a mixture that has a positive temperature coefficient for surface tension rather than the negative coefficient of most other working fluids. The positive surface tension coefficient led to the occurrence of a “self-rewetting” phenomenon that helped prevent the dry out of heated surfaces. Based on earlier studies, we investigated the use of a self-rewetting working fluid in a PHP made from a multiport extruded aluminum pipe. Although the main driving force for the fluid motion in a PHP is pressure fluctuations due to rapid bubble nucleation and growth in the heated section and condensation in the cooled section, generating a slug flow in a serpentine channel, the self-rewetting phenomenon was expected to have some influence on the PHP performance. In addition, the experiment was carried out under conditions of a severe actuation situation for the heat pipe. These experimental
results have not been previously reported. In this study, the
effects of the alcohol concentration, fluid fill ratio, and heat
pipe orientation on heat transport rates were reported for a self-
rewetting fluid using heptanol.

**EXPERIMENTAL APPARATUS AND PROCEDURE**

The experimental apparatus is shown in Figure 2. It consists
of a PHP, a syringe used to fill the heat pipe with a working
fluid, a vacuum pump, a cartridge heater block, an aluminum
fin, a cooling fan, and a data acquisition system. The heat pipe
was made from an extruded flat aluminum multiport tube
(manufactured by Brazeway) that was 240 mm long, 16 mm
wide, and 2.0 mm thick. A photograph and the dimensions
of the cross section of the PHP are shown in Figure 3. There are 9
square channels with a cross section of 1.4 mm × 1.0 mm and a
wall thickness of 0.37 mm between the neighboring channels.
The heat pipe was constructed with the multiport tube by
machining and welding the ends of the channels to form a
single serpentine channel with a total internal volume of 4.0 ml.
The heat pipe was then oriented vertically and horizontally with
the cartridge heater attached to the 60 mm long evaporator
section at the bottom; a cooling fin was attached to the 60 mm
long condenser section. Between the evaporator and the
condenser sections was a 120 mm long adiabatic section. The
entire heat pipe, excluding the cooling fin, was insulated with
20 mm thick polystyrene layers and glass wool. The fin and the
cartridge heater block were attached to the heat pipe surfaces
with a thin layer of thermal grease. A fan driven by a DC 12 V
motor was placed in front of the fin at different distances to
provide a cooling air flow (22°C–25°C) at a velocity of 4.2 m/s.
The power supplied to the cartridge heater block was varied
from 0 to 40 W. A three-way valve was attached to the heat pipe
at the top to allow for vacuuming and filling the heat pipe with
a working fluid using a syringe.

To measure the temperatures of the heat pipe, seven J-type
thermocouples with a wire diameter of 0.1 mm were attached to
the heat pipe surface at two locations in the evaporator section
\(T_{\text{eva}}, T_1\), two locations in the condenser section \(T_{\text{con}}, T_3\), and
five equidistant locations in the adiabatic section \(T_2, T_4, T_5\). In
addition, the heater and air temperatures \(T_h, T_{\text{air}}\) were
measured. All the thermocouple signals were sampled and
recorded using a PC-based data acquisition system at a
frequency of 1 Hz. The self-rewetting working fluid was
prepared by adding heptanol to de-ionized water to prepare an aqueous solution of specified mass concentrations.

In charging a PHP to a specified fill ratio, the heat pipe was first vacuumed to a pressure of –98 kPa by a gauge; by turning the three-way valve, specific amounts of the working fluid were injected from the syringe. The mass of the heat pipe was weighed using an electronic balance before and after the filling operation to confirm the fill ratio. The power supplied to the cartridge heater block was adjusted after the heat pipe reached a steady-state temperature condition over its entire surface. When either a dry out condition or the evaporator section temperature of 100°C was reached, the experiment was terminated by switching off the heater (for experiment safety). Experiments were conducted for modifying parameters such as the evaporator temperature (25°C–100°C), filling ratio (0–60 vol%), PHP orientation angle (0° (horizontal) or 90° (vertical)), and heptanol concentration in the working fluid (0, 0.1, 0.6, and 1.0 wt%). The uncertainties were as follows.

- Temperature readings: ± 2.5%
- Filling ratio: ± 0.6%
- Self-rewetting fluid concentration: ± 0.1%
- Heater power: ± 0.1%
- Thermal resistance: ± 2.5%

RESULTS AND DISCUSSION

1. Self-Rewetting Fluid

The thermophysical properties of the working fluid are shown in Table 1. The surface tension of aqueous solutions containing heptanol (C7H16O) is known to have unusual variations with temperature. Figure 4 shows the variations of surface tension with temperature for heptanol, water, and its aqueous solution [10]–[12]. In contrast to water—for which the surface tension decreases monotonically with increasing temperature—the surface tension of the aqueous solution decreases gradually; it reaches a minimum value at approximately 40°C before gradually increasing at higher temperatures. Based on the positive temperature coefficient at temperatures above 40°C, the aqueous solution may have a positive effect on the heat transport performance due to the altered boiling behavior and surface-tension-driven convection. Figure 5 illustrates the surface flows directed from cold to hot regions caused by the very large positive surface tension gradient due to temperature. The flow is opposite to ordinary Marangoni convection.

2. Maximum Heater Power

The maximum heater power is defined here as the heater power achieved when the temperature of the evaporator section reaches 100°C and the experiment is terminated. Figures 6 and 7 show the relationship between the maximum heater power (Q) and the fill ratio (FR) for different aqueous solution concentrations (C) and different installation angles for the PHP. The values shown indicate the average value of the maximum heater power when the same experiment was repeated more than three times. In Figure 6, compared with the PHP test results obtained by other researchers, the maximum heater power (Q) was quite low. In addition, it decreased as the fill ratio increased. This was probably because the distance between the evaporation and the condensation sections of the testing PHPs was extremely long. In addition, there was no liquid available for transporting sensible heat in the liquid...
slugs. In general, the PHP performance decreased as the PHP length increased and the bend section of the channel decreased [13]. However, all the maximum heater powers, except for the zero fill ratios, were higher than that for pure water. In contrast, at the same fill ratios, a heptanol concentration of 0.1 wt% provided improved performance compared to pure water. At higher heptanol concentrations (1.0 wt%), the maximum heater power increased significantly. This was due to the reduction in the heater and evaporation section temperatures, which allowed greater heater power to be applied without exceeding the 100°C limit.

For the horizontal setup, as shown in Figure 7, the maximum heater power for pure water did not change and stayed low even at high fill ratios. This implies that the PHP does not work with this condition. On the other hand, for the

3. Temperature Distribution

Figure 8 shows the temperature history obtained for the working fluids of (a) 0 wt% (water) and (b) heptanol (C = 0.1 wt%). The fill ratios and orientation of the PHP are 30 vol% and vertical (= 90°), respectively. The y- and x-axes show the temperature and time, respectively (for 5 min of the steady state). The right vertical axis shows the coordinate of the supply heater power (bold line). Comparing each graph, by mixing the self-rewetting fluid, the heater temperature ($T_h$) and evaporator temperature ($T_{eva}$) are generally lower, and the evaporator and heater temperature difference ($\Delta T = T_{eva} - T_{con}$) of the
condensed part also decreases. Similar results were obtained in the other tests with different fill ratios. For the heptanol aqueous solution (b), since self-induced vibration is generated even if the supply capability is small, the PHP temperature difference decreases. In particular, the temperature distribution in the high-temperature range at 20 W of the supply capability was clearly lower than that for water. The heat transport condition when using the heptanol aqueous solution (b) was satisfactory in the high-temperature range. According to Wijk [14], the changes observed can be attributed to the changes in boiling and slug flow characteristics due to the self-rewetting fluid. The nucleation of bubbles, their growth, and their departure are affected by the liquid behavior on the heated surface. The reductions in the heater and evaporator section temperatures indicate improved heat transfer from the heater to the working fluid and reduced thermal resistance. Although slug flow characteristics such as slug length and frequency have not been measured, the improved heat transport performance suggests more vigorous pulsating motion occurring inside the PHP filled with the self-rewetting fluid.

Figure 9 shows the temperature history for the horizontal orientation obtained for the working fluid of water (C = 0 wt%) and heptanol (C = 0.1 wt%). The experimental conditions and the axis of the figure are identical to those described for Figure 8, except that only the PHP is set up in a horizontal orientation. In comparing each graph, by mixing the self-rewetting fluid, the heater temperature (T_h) and evaporator temperature (T_eva) are slightly lower, and the evaporator and heater temperature difference (∆T = T_eva – T_con) of the condensed part also decreases slightly.

4. Temperature difference
The temperature difference between the evaporator and the condenser sections is shown in Figure 10. The fill ratios and orientation of the PHP are 20 vol% and vertical (90°), respectively. The experimental parameter being adjusted was the heptanol concentration. The temperature difference decreased with an increase in the heat quantity supplied, after which a constant value was maintained. Moreover, the temperature difference decreased when the self-rewetting fluid was mixed in compared with pure water. However, an optimum value was proven to exist for adulterating the solution because the temperature difference for 0.1 wt% decreased the most.

Figure 11 also shows the temperature difference for the horizontal orientation. The experimental conditions and axis of the figure are identical to those described for Figure 10, except that the PHP is set up horizontally. This figure shows that the effect of the self-rewetting solution appears when Q ≥ 5 W, and the heptanol concentration of 0.1 wt% decreases most as well as Figures 10.
5. Thermal Resistance

The thermal resistance $R$ of the heat pipe (K/W) was calculated from the heater power $Q$ and the temperature difference between the evaporator and condenser sections ($\Delta T = T_{eva} - T_{con}$).

$$R = \frac{\Delta T}{Q}$$  \hspace{1cm} (1)

Figure 12 shows the thermal resistance data of the heat pipe with different fill ratios. The heptanol concentration of the working fluid and the PHP orientation are 0.6 wt% and vertical (90°), respectively. The thermal resistance decreased with an increase in the heater power. At all heater power levels, the thermal resistance was found to decrease with the fill ratios. This implies that the PHP operates even when there is a low temperature difference at low fill ratios, depending on the effect of the self-rewetting fluid. Similar results were obtained in other tests with different heptanol concentrations.

6. Theoretical Analysis for Self-Rewetting Effectiveness

When heat is added to the PHP, the oscillating motion combined with the phase-change process transfers heat from the evaporating section to the condensing section. The most commonly encountered operating limit problem in the PHP is the capillary pressure limit. The capillary pressure at the liquid-vapor interface is due to the curvature of the meniscus and the surface tension of the working fluid; it is given by the Young-Laplace equation [15]. The capillary pressure is

$$\Delta P_{cap} = \frac{2\sigma}{r} \cos \theta$$  \hspace{1cm} (3)

where $\theta$ is the apparent contact angle, and $r$ is the capillary radius. According to Zhang [8], based on Eq. (3), the following equation can be derived:

$$\frac{\partial \Delta P_{cap}}{\partial T_v} = \frac{2}{r} \cos \theta \frac{\partial \sigma}{\partial T_v} - \frac{2}{r} \sin \theta \frac{\partial \theta}{\partial T_v} \cos \theta$$  \hspace{1cm} (4)

where $T_v$ is the vapor temperature for the evaporator section. From this equation, when the operating temperature of the evaporator is increased, the capillary pressure pumping head increases for the positive surface tension gradient with increasing temperature and decreasing contact angle. As a result of the positive surface tension gradient increasing with the temperature of the self-rewetting fluid, the working fluid tends to move toward the hot region in the PHP and consequently increasing the heat load.

CONCLUSION

A series of experiments were performed to investigate the improvement in performance resulting from the use of a self-rewetting fluid in a PHP. By adding heptanol to water to produce a self-rewetting working fluid, the effects of heptanol concentrations and fill ratios on the thermal resistance, maximum heater power, and other parameters were investigated. The following conclusions were drawn from the resulting experimental data:

1. The self-rewetting fluid improved the heat transfer characteristics in the evaporator section to reduce the temperature difference between the heater and the evaporator section of the PHP, resulting in lower thermal resistance of the heat pipe compared to a water-filled PHP.

2. It is possible to obtain low thermal resistance for a self-rewetting fluid solution with a concentration of 1 wt% or less as the working fluid compared to pure water.

NOMENCLATURE

- $C$ : Mass concentration, wt%
- $FR$ : Fill ratio, vol% ($= V_{liq}/V_{tot}$)
- $P$ : Pressure, N/m²
- $Q$ : Heater power, W
- $R$ : Thermal resistance, K/W
- $r$ : Radius, mm
- $T$ : Temperature, °C
ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support given by a research grant from the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (C), 20560205, 2008.

REFERENCES


