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Study on a Pulsating Heat Pipe With Self-Rewetting Fluid

This paper discusses a pulsating heat pipe (PHP) using a self-rewetting fluid. Unlike other common liquids, self-rewetting fluids have the property that the surface tension increases with temperature. The increasing surface tension at a higher temperature can cause the liquid to be drawn toward a heated surface if a dry spot appears and thus to improve boiling heat transfer. In experiments, 1-butanol and 1-pentanol were added to water at a concentration of less than 1 wt % to make self-rewetting fluid. A pulsating heat pipe made from an extruded multiport tube was partially filled with the self-rewetting fluid water mixture and tested for its heat transport capability at different input power levels. The experiments showed that the maximum heat transport capability was enhanced by a factor of 4 when the maximum heater temperature was limited to 110°C. Thus, the use of a self-rewetting fluid in a PHP was shown to be highly effective in improving the heat transport capability of pulsating heat pipes.
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1 Introduction

Advanced cooling technologies are needed to remove higher heat fluxes from microelectronic devices containing microchips of increased circuit density [1]. Advancing the heat transport technology is one of the key factors in achieving improved cooling of microelectronic components. Heat pipes that 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 [2], a counter-stream-mode oscillating-flow heat pipe [3], and a pulsating heat pipe (PHP) [4–6] have been developed and investigated for various heat removal applications. The PHP investigated in this study is subjected to evaporation and condensation of the working fluid, both of which induce pressure fluctuations and self-oscillation of the working fluid in a serpentine channel. It is a fully passive device, but the driving force does not depend on the surface tension, unlike wicked or grooved capillary heat pipes [7–13]. Recently, Abe [14] conducted an experimental investigation of heat transport enhancement using an aqueous alcohol solution in a wicked heat pipe. The working fluid consisted of water and a small amount of alcohol, a mixture that had a positive temperature coefficient of surface tension rather than the negative coefficient in most other working fluids. The positive surface tension coefficient leads to a "self-rewetting" phenomenon that helps prevent the dryout of heated surfaces. Based on earlier studies, we investigated the use of a self-rewetting working fluid in a pulsating heat pipe made of a multiport extruded aluminum pipe (manufactured by Brazeway). 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, which generate a slug flow in a serpentine channel, the self-rewetting phenomenon was expected to have some influence on the pulsating heat pipe performance, especially at high heat fluxes near the dryout condition. No such experimental results have been reported. In this work, the effects of alcohol concentration and fill ratio (FR) on heat transport rates are reported.

2 Experimental Apparatus and Procedure

The experimental apparatus is shown in Fig. 1. It consists of a pulsating heat pipe, 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 of an extruded flat aluminum multiport tube, 145 mm long, 25 mm wide, and 2.0 mm thick. A photograph and dimensions of the cross section are shown in Fig. 2. There are 13 square channels with a cross section of 1.26×1.26 mm^2, 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 2.95 ml. Then, the heat pipe was oriented vertically with a cartridge heater attached to the 50 mm long evaporator section at the bottom, and a cooling fin was attached to the 50 mm long condenser section. Between the evaporator and condenser sections was a 45 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 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 cooling air flow (22–25°C) at a velocity of 0–5.2 m/s. The power supplied to the cartridge heater block was varied from 0 W to 140 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, five 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_{eva}, T_1), two locations in the condenser section (T_{con}, T_7), and five equidistant locations in the adiabatic section (T_2–T_6). Additionally, the heater temperature (T_h) and air temperature (T_{air}) were measured. All the thermocouple signals were sampled and recorded by a PC-based data acquisition system at a frequency of 3 Hz. The self-rewetting working fluid was prepared by adding 1-butanol or 1-pentanol to deionized water to prepare an aqueous solution of specified mass concentrations.

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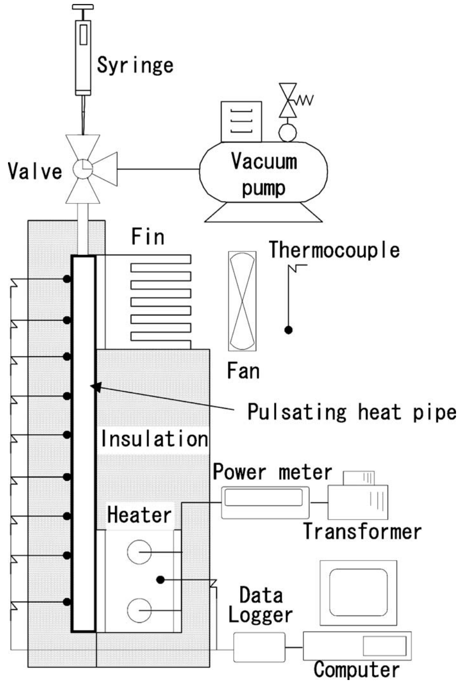

Fig. 1 Experimental apparatus

In charging a pulsating heat pipe to a specified fill ratio, the heat pipe was first vacuumed to a pressure of −98 kPa by a gauge, and by turning the three-way valve, a specified amount of the working fluid was 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 a steady state temperature condition was reached over the entire surface of the heat pipe. When either a dryout condition or the evaporator section temperature of 110°C was reached, the experiment was terminated by switching off the heater. Experiments were conducted for the evaporator temperature range of 25–110°C, filling ratio of 0–50 vol % , and concentrations of 1-butanol in the working fluid of 0 wt %, 0.1 wt %, 0.25 wt %, 0.5 wt %, and 1.0 wt %. The measurement uncertainties in the present work are as follows.

- temperature readings: ±2.5%
- filling ratio: ±0.4%
- self-rewetting fluid concentration: ±0.02%
- heater power: ±1.0%
- thermal resistance: ±3.7%

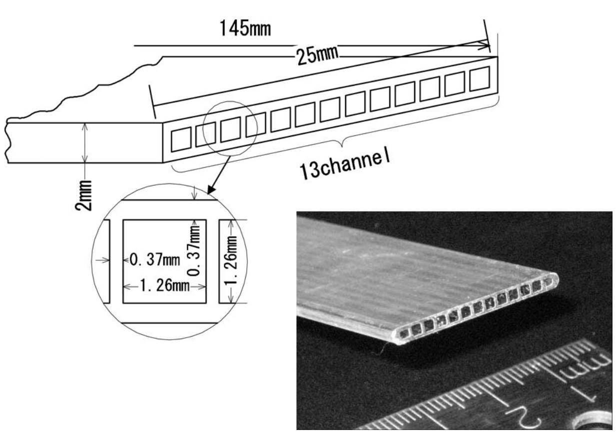

Fig. 2 Aluminum tube used to construct a pulsating heat pipe

Table 1 Properties of working fluid

	Working fluid (at 20°C, 0.1 MPa)		
	Water	1-Butanol	1-Pentanol
Molar mass (kg/kmol)	18.0153	74.1216	88.15
Density (kg/m^3)	998.2	809.8	814.4
Boiling point (°C)	100	117.73	137.99
Solubility in water (ml/ml)	–	9.1/100	3.32/100

3 Results and Discussion

3.1 Self-Rewetting Fluid. The thermophysical properties of the working fluid are shown in Table 1. 1-butanol ($C_4H_{10}O$) and 1-pentanol ($C_5H_{12}O$) are alcohols, and the surface tension of their aqueous solutions is known to have unusual variations with temperature. Figure 3 shows the variations in surface tension with temperature for 1-butanol, 1-pentanol, water, and its aqueous solution [15,16]. In contrast to water, pure 1-butanol and pure 1-pentanol show monotonically decreasing surface tension values with temperature, and the surface tension of an aqueous solution decreases gradually, reaching a minimum value at approximately 70°C and gradually increasing at higher temperatures [17]. Based on the positive temperature coefficient at temperatures above 70°C, the aqueous solution may have a positive effect on heat transport performance due to the altered boiling behavior and surface-tension-driven convection.

3.2 Maximum Heater Power. The maximum heater power is defined here as the heater power achieved when the temperature of the evaporator section reached 110°C, and the experiments were terminated. Figures 4 and 5 show the maximum heater power (Q) and the FR for different aqueous solution concentrations (C) of butanol and pentanol, respectively, in the working fluid. The values shown indicate the average value of the maximum heater power, and the error bars for some data points indicate the scatter in the data obtained when the same experiment was repeated more than four times. In Fig. 4, the maximum heater power increased with the increase in the fill ratio probably because more liquid was available for transporting sensible heat in the liquid slugs. In contrast, for the same fill ratio, the butanol concentration of 0.1 wt % did not improve the performance compared with the pure water case. At higher butanol concentrations, 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.

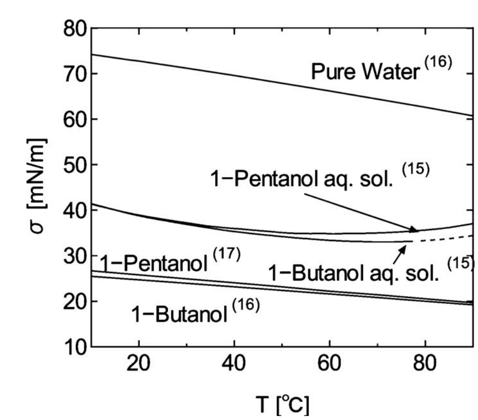

Fig. 3 Surface tension of water, 1-butanol, 1-pentanol, and its aqueous solution

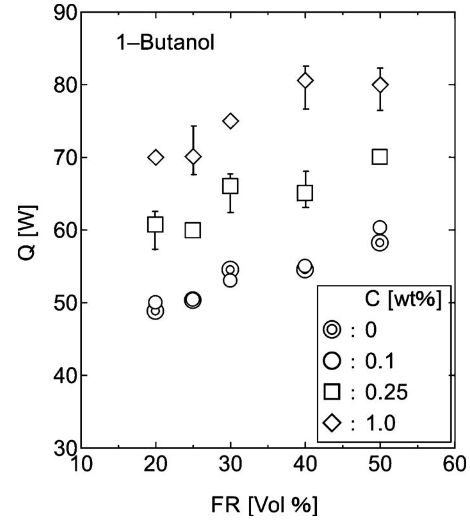

Fig. 4 Maximum heater power obtained for different fill ratios (1-butanol)

In the case of the pentanol aqueous solution, shown in Fig. 5, the maximum heater power increases even in 0.1 wt % concentration in comparison with that of pure water (C=0%). Moreover, the largest heater power of the pentanol aqueous solution is approximately 1.2 times higher than that of the butanol aqueous solution at the same solution concentration. In addition, it is shown that the supply heater power at FR=40 vol % obtains a maximum value in spite of the aqueous solution concentration of the pentanol. In the solution concentration over 0.25 wt %, the maximum heater power decreases. In particular, in 1.0 wt %, the maximum heater power is equal to the value of water, except for FR=40 vol %. At present, it is difficult to explain the difference between the maximum heater powers by butanol and pentanol. However, a microscopic observation with controlled parameters will be carried out in the future.

3.3 Temperature Distribution. Figure 6 shows the temperature history obtained for the working fluid of (a) 0 wt % (water), (b) butanol (C=0.25 wt %), and (c) pentanol (C=0.25 wt %). All the fill ratios are 20 vol %. The *y*-axis and the *x*-axis show the temperature and time, respectively (for 60 s of the steady state).

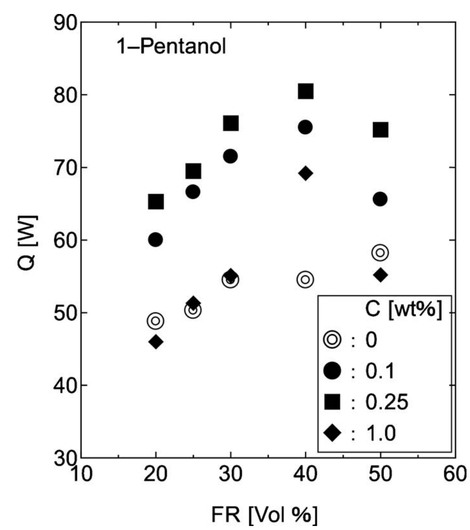

Fig. 5 Maximum heater power obtained for different fill ratios (1-pentanol)

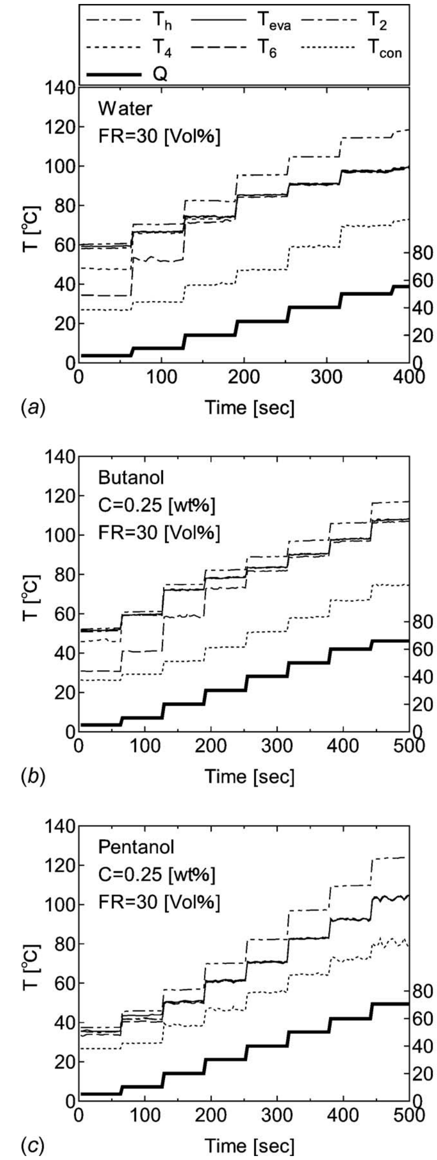

Fig. 6 Variation in PHP temperature for water and self-rewetting aqueous solution

The right vertical axis shows the coordinate of the supply heater power (bold line). In the comparison of 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 other tests with different fill ratios. In the case of the pentanol aqueous solution of (c), since self-induced vibration is generated even if the supply capability is small, the PHP temperature difference decreases. However, the heat transport condition in using the butanol aqueous solution (b) is satisfactory in the high-temperature range. The changes observed are attributed to the changes in boiling and slug flow characteristics due to the self-rewetting fluid. The nucleation of bubbles, their growth, and 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 trans-

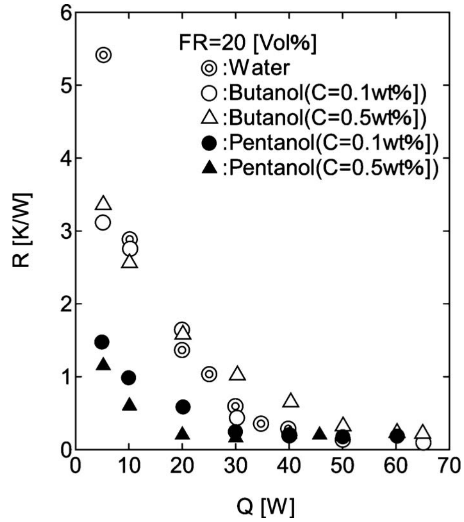

Fig. 7 Variation in thermal resistance with heater power at different working fluids

port performance suggests more vigorous pulsating motion occurring inside the pulsating heat pipe filled with the self-rewetting fluid.

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

$$R = \Delta T/Q \quad (1)$$

Figure 7 shows the thermal resistance data for a water-filled heat pipe with different working fluids and concentrations. The working fluids are water, butanol, and pentanol. Their aqueous solution concentrations (C) are 0.1 wt % and 0.5 wt %, respectively, and all the fill ratios are 20 vol %. The thermal resistance decreases with increasing heater power. At the low heater power level, the thermal resistance was found to be lower than that obtained in the pure water case, most likely due to the earlier onset of pulsating motion and reduced temperature in the evaporator section. This means that the PHP operates even at a low-temperature difference depending on the effect of the self-rewetting fluid. It is also shown that the effect on thermal resistance by the self-rewetting fluid solution concentration is not strong at the high heater power level.

4 Conclusion

A series of experiments was performed to investigate the performance improvement resulting from the use of a self-rewetting fluid in a pulsating heat pipe. By adding 1-butanol or 1-pentanol to water to produce a self-rewetting working fluid, the effects of the butanol and pentanol concentrations and fill ratios on the thermal resistance, maximum heater power, and other parameters were investigated. The following conclusions can be drawn from the current experimental data.

1. The self-rewetting fluid improved the heat transfer characteristics in the evaporator section, so that the temperature difference between the heater and evaporator section of the pulsating heat pipe was reduced, resulting in lower thermal resistance of the heat pipe compared with the water-filled PHP.
2. Pentanol aqueous solution makes a self-pulsating motion at a temperature difference that is lower than that of butanol aqueous solution and pure water.
3. It is possible to obtain low thermal resistance by a solution concentration using self-rewetting fluid solution of 1 wt % or less as the working fluid, compared with that of pure water.

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Nomenclature

C = mass concentration, wt %
FR = fill ratio, vol %$(=V_{liq}/V_{tot})$
Q = heater power, W
R = thermal resistance, K/W
T = temperature, °C
ΔT = temperature difference, °C

Subscripts

1–7 = thermocouple location
air = air
con = condenser section
eva = evaporator section
h = heater
liq = liquid
tot = total

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