Prototype Experiment on Cooling Performance of a JEST-type Loop Heat Pipe

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Abstract: The cooling of such high-performance electronic devices as CPUs and power semiconductors is one technical challenge that significantly affects the practical applications of electronic hardware mounting them. In recent years, the heat density of these devices has significantly increased due to higher output and downsizing. The required cooling performance for such high-performance electronic devices will increase even more in the near future. Therefore we propose a new cooling technology called a JEST-type Loop Heat Pipe (JEST-LHP) that satisfies the required performance: higher output and higher heat density. Similar to conventional loop heat pipes, this new heat pipe consists of an evaporator section, a condenser section, and two pipes (a vapor line and a liquid line) as well as the Jet Explosion Stream Technology (JEST) that enhances the heat transfer in the evaporator section. We fabricated a prototype heat pipe and conducted fundamental experiments on the cooling performance. In our experiments, the evaporator section was heated by a small heater whose heating area was 400 mm², and the condenser section was air-cooled by a fan. Water was employed as the working fluid. Our experimental results confirmed that the maximum heat transport rate of our present heat pipe was 780 W. This value corresponds to a heat flux of 195 W/cm², and we obtained a total thermal resistance of 0.130 K/W.

Keywords: Loop Heat Pipe, Two-Phase Heat Transfer, JEST, Evaporation, Electronics Cooling

Introduction:
In recent years, the cooling technology of high-performance electronic devices, which are typified by Central Processing Unit (CPUs) and power semiconductors, has become a key technology for practical application. Air cooling apparatus combining heat pipes (HPs) and fans are used for cooling such high heat density electronic equipment. HPs are a natural circulation type cooling device. One HP characteristic is using the latent heat of the working fluid that can transport the heat from an introducer section to a condenser section with a small temperature difference between condenser and evaporator. The HPs have been used as promising cooling technologies that can handle high heat density.

However, cooling performance of HPs has reached limit since 2005, because the heat density of CPUs had increased to more than 100W/cm². Therefore, development of the higher power CPUs has avoided [1]. In addition, Insulated Gate Bipolar Transistors (IGBTs) have been used for motor-driven vehicles such as an electric or a hybrid electric. And water-cooling technology has been used to cool the many IGBTs. The water cooling technology uses large heat-receiving blocks with distributed elements for decreasing heat density. Miniaturization to reduce the weight of cooling devices themselves is another critical technical issue. Future cooling technology must be able to handle large capacity, small size and high heat density.

The authors have proposed Jet Stream Explosion Technology (JEST) type Loop Heat Pipe (JEST-LHP) cooling system to establish a new cooling technology that can handle to high heat density with large capacity for future electronic devices. The JEST-LHP prototype is equipped with an air-cooled heat exchanger in its condenser section. The main feature of prototype is as follows:

1: The JEST-LHP is comprised of an evaporation section, a vapor line, a condenser section, and a liquid line.
2: The JEST-LHP is a natural circulation type heat transport device. In the JEST-LHP, both vapor and liquid working fluids are thermally transported to the condenser part as a vapor-liquid mixed phase flow.
3: The evaporation section has a check valve and an introduction pipe for the working fluid. For cooling, the evaporation section is not always filled with liquid.

In this report, the experimental results of the prototype JEST-LHP are introduced on the basic performance of the evaporator section and the technical level is verified.

Experimental Apparatus and Experimental Method:
The structure of a JEST-LHP that was prototyped in this study is shown in Fig. 1. The JEST-LHP is configured as a loop with a condenser section, a liquid line, an evaporator section, and a vapor line. The loop is the circulation path of the working fluid. The inlet and outlet of the evaporator and condenser sections are copper, and the other part (the liquid and vapor lines) is a transparent perfluoroalkoxy alkane (PFA) tube to visualize the internal working fluid.
The inner diameter of both the liquid and vapor lines is 7.53 mm. The dimensions of the outer shape are shown in Fig. 1.

The lower surface of the evaporator section (the heated surface) is a copper heat-receiving plate, and the upper surface is covered with a copper lid. The check valve, which is a special feature of the JEST-LHP, is placed between the evaporator section and the liquid line. The introduction pipe is in the evaporator section. The condenser section is an air-cooled heat exchanger that has a fin tube with two fans having a diameter of 80 mm. The volume flow ratio was 160m³/h through the fin tube. The heating unit is made of a copper block in which cartridge heaters are embedded. The size of the heating surface size A is 400 mm². Also, the heating block has three holes equally spaced. The 1-mm diameter thermocouples were inserted into the holes. This heating unit, which can input heat quantity from 0 to 1000 W, contacts the evaporator part through silicone grease (thermal conductivity 0.9W/(m·K)).

The configuration inside the evaporator section is shown in Fig. 2. The heating surface and the introduction pipe of the working fluid are closely-apposed to exhibit the following three characteristics:

A) The check valve automatically opens and closes by balancing the pressure by vapor generation in the evaporator section and the water head pressure of the working fluid in the liquid line. The working fluid is sequentially supplied to the evaporator section.

B) The working fluid, which was dropped to the heating surface from its introduction pipe, is partly vaporized by the receiving heat. The vaporized working fluid causes a large volume expansion; but since the check valve prevents backflow into the liquid line, the working fluid flow is one-way to the heating surface.

C) There is a small gap between the heating surface and the introduction pipe. And the working fluid of vapor and non-boiling liquid passes through the gap. The working fluid is evaporated radially to the heating surface at high velocities. The thin film of liquid-phase working fluid is made on the heating surfaces, and the working fluid evaporation is accelerated.

As described above, the experiments were conducted under this configuration to verify the expected effect. The following temperatures were measured in this experiment, see Fig. 1:

- $T_{h1}$, $T_{h2}$, $T_{h3}$: heating unit internal temperature
- $T_{vout}$: vapor line outlet temperature
- $T_{lin}$: liquid line inlet temperature
- $T_E$: vapor temperature at evaporator
- $T_A$: ambient temperature

The working fluid of the system is water. After the internal system pressure was lowered to less than 1 kPa, the working fluid was enclosed from a supply port at the vapor line. After that, the supply port was opened, and internal system pressure was increased to the atmosphere pressure. The system pressure was reduced to the working fluid saturated vapor pressure, and sealed. The heat quantity was increased at regular intervals and checked by a wattmeter. The heat quantity was calculated from the temperature gradient that was measured with inserted sheath thermocouples. Heating surface temperature $T_H$ was calculated from the temperature difference from $T_{h1}$ to $T_{h3}$ and the material thermal conductivity (copper, 390W/(m·K)). The experiment was ended when the heating surface temperature continued to rise. At the limited heat quantity, the heating surface temperature $T_E$ is stable. Heat quantity is increased than maximum, the temperature continues to rise. Table 1 summarizes the experimental conditions of this experiment.
Results and Discussion:
Temperature distribution

Fig. 3 shows the temperature distribution of each part of the experimental apparatus when the heat quantity was changed. The working fluid amount was 85 g. The each mean temperature was calculated for 10 minutes when the each temperature is stabled at the each heat quantity. It was found that the ambient temperature $T_A$ is constant at about 25°C, and the other temperatures increased with the heat input. Liquid line inlet temperature $T_{Lin}$ is cooled to near the ambient temperature $T_A$ at the condenser section. The increase in temperature at the evaporator section $T_E$ was 16~31°C. The increase of $T_E$ was more than the increase of $T_{Lin}$. It depends on each heat quantity $Q$. Heating surface temperature $T_H$ also increased with the increase in heat quantity $Q$.

The temperature difference between the temperatures at the maximum ($Q$=780W) and minimum ($Q$=170W) heat quantities was about 57°C. The JEST-LHP was stable operating at $T_H$=125°C and the heat quantity $Q$ was 780 W as the maximum heat quantity. When the working fluid, which flows out from the evaporator section, moves to the condensation section through the vapor line, vapor line outlet temperature $T_{Vout}$ was about 10°C lower than vapor temperature $T_E$. This result was probably caused by the influence of the pressure loss due to the working fluid flow in the vapor line.

Thermal resistance:
The relation between heat quantity $Q$ and system thermal resistance $R$ is shown in Fig. 4. In Fig.4, $Q$-$R$ relation depends on the working fluid amount. The working fluid amount $V_w$ is 35, 45, 65, and 85 g. The system thermal resistance $R$ was calculated by the following equation:

$$ R = \frac{T_H-T_A}{Q} \tag{1} $$

With the increase in the heat quantity, the system thermal resistance $R$ becomes smaller. The result of system thermal resistance $R$ at each working fluid amount $V_w$ is only within about 5% error. The effect of changing working fluid amount on system performance is small. In addition, the more working fluid in the system, the higher the heat quantity is. Dry-out is caused by insufficient working fluid, and heated surface temperature continues to rise. The maximum heat quantity $Q$ of this experiment was about 780 W when the working fluid amount was 85 g. At that time, the system thermal resistance was about 0.130 K/W, and the heat density was 195W/cm².

Heat transfer coefficient at evaporator

Fig. 5 shows the relation between the heat transfer coefficient $h$ at the evaporator section and heat quantity $Q$ for each working fluid amount $V_w$. The heat transfer coefficient $h$ at evaporator section was calculated by equations (2) and (3):

$$ h = \frac{Q}{A'\Delta T} \tag{2} $$

$$ \Delta T = T_H' - T_E \tag{3} $$

Here, $\Delta T$ : temperature difference

<table>
<thead>
<tr>
<th>Table 1 Experimental conditions</th>
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<tr>
<td>Working fluid</td>
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<tr>
<td>Working fluid amount [g]</td>
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<tr>
<td>Volume flow ratio from fan [m³/h]</td>
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<tr>
<td>Heat quantity [W]</td>
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<tr>
<td>Contact area with heating surface [mm²]</td>
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<tr>
<td>Liquid and vapor line inner diameter [mm]</td>
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Fig. 3 Temperature distribution of each part for each heat quantity

Fig. 4 System thermal resistances of each working fluid amount

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\( T_{H'} \) : heated surface temperature  
\( T_E \) : vapor temperature at the evaporator  
\( A' \) : heated surface area

The area of \( A' \) is 576mm², which was calculated by 45° heat spreading angle on the heat-receiving plate that received heat from the heater unit. The contact thermal resistance between the heated surface and the heater is neglected. Heating surface temperature \( T_{H'} \) was calculated from inside heater temperatures \( T_{h1} \) and \( T_{h3} \). The heat-receiving surface temperature inside the evaporator section \( T_{H'} \) was calculated by the heat-receiving plate thickness and the thermal conductivity of the heated plate material. In Fig. 5, the heat transfer coefficient \( h \) at the evaporator section rose with increasing heat quantity \( Q \) in any working fluid amount \( V_m \). The heat transfer coefficient \( h \) at the evaporator section was from 10000 to 20000W/(m²·K).

As described above, the maximum heat density was 195W/cm², and the heat transfer coefficient \( h \) at the evaporator section reached 20000W/(m²·K). Therefore, the JEST-LHP was developed as a prototype of new cooling system with a natural circulation cooling technology.

**Conclusion:**
A prototype JEST-LHP which has an air-cooled heat exchanger in the condenser section was developed. The basic performance was confirmed with a heated area of 400mm² and the following findings were obtained:

1) The stable operation was confirmed in the range of 170 to 780W.
2) The maximum heat quantity at 85 g of working fluid amount was 780 W, the heated surface temperature was about 125°C, and the system thermal resistance was 0.130 K/W. The heat density reached 195W/cm².
3) The maximum heat transfer coefficient in the evaporator section reached 20000W/(m²·K) when the heat quantity was about 780 W.

**Reference:**