Contribution to the achievement of SDGs
by Furukawa Electric Group

The Development of Heat-Pipe for Top Heat

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ABSTRACT Along with improvement of performance of electronic devices, thermal problems caused by the high heat generation and the high-density packaging have been widely recognized and the heat radiation measures have become important subjects. The heat radiation design has been diversified and our improvement of the heat pipe performance at the top heat condition will contribute to the improvement of flexibility in the heat radiation design. We analyzed the pressure drop in heat pipes and applied copper powder which had a high capillary pressure and copper short fiber which had a high transmission rate to their wick, and we have successfully developed the heat pipe which improved its performance lowered by gravity to raise its heat transfer rate. In this paper, we will introduce our technology about the heat pipe for the top heat condition.

1. INTRODUCTION

The heat radiation measures have become an important subject in the design of electronic devices. Recently, along with the improvement of performance of electronic devices, thermal problems caused by the high heat generation and the high-density packaging have been widely recognized and its heat radiation design has become more difficult year after year. A heat pipe heatsink installed with heat pipes which were highly efficient heat transfer devices has been applied to various products as a heat radiation device1), 2).

However, we have a problem in the condition of “top heat”, where an evaporation portion of a heat pipe is located higher than its condensation portion, so that the heat transfer rate of the heat pipe is largely reduced by the effect of gravity. In other words, in the case where the heat generating source to be cooled is located at a higher position compared with air-cooling fins or a water-cooling portion, it is difficult for a heat pipe to show its proper heat transfer performance, and its application to devices is limited.

With that in mind, we have developed the heat pipe which is able to maintain a sufficient heat transfer rate even under the top heat condition. In this paper, we will explain the internal structure and the working principle of the heat pipe whose heat transfer rate under the top heat condition has been improved.

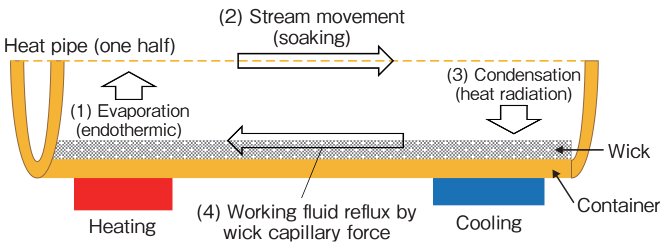

Figure 1 (a) **Sketch of the heat pipe operation.**

2. WHAT IS THE TOP HEAT

Inside the heat pipe as shown in Figure 1, its working fluid is changing from liquid to vapor state at its evaporation portion and flows from the evaporation portion to the condensation portion (cooling portion), and the working fluid is changed from vapor to liquid state at the condensation portion and returns to the evaporation portion. In such a way as mentioned above, the heat transfer by latent heat in a tubular container is carried out between

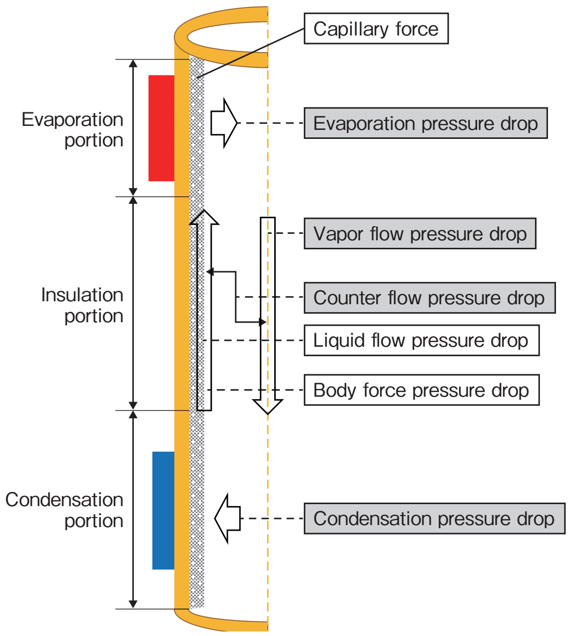

Figure 1 (b) **The pressure drops in a heat pipe.**

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the evaporation portion and the condensation portion in accordance with the circulating flow formed between the evaporation portion and the condensation portion. In case of the operation in the top heat condition, the reflux of the working fluid is carried out by the capillary pressure and its maximum heat transfer rate is determined by the following balance equation shown below[3].

Capillary pressure = Evaporation pressure drop
+ Vapor flow pressure drop
+ Condensation pressure drop
+ Liquid flow pressure drop
+ Counter flow pressure drop
+ Body force pressure drop
caused by gravity

The performance of a wick is a determining factor of the capability of a heat pipe, because the capillary pressure and each of the pressure drops are determined by the wick structure inside the heat pipe. Such a wick has been applied to a traditional heat pipe used under the top heat condition where a copper powder was sintered over its full length as shown in Figure 2 (a). The sintered copper powder was able to transport the heat against the pressure drop of the body force caused by the gravity even when applied under the top heat condition, because it had a large capillary pressure. On the other hand, the maximum value of heat transfer (maximum heat transfer rate) of the sintered copper powder is small, because it has a smaller transmission factor of liquid to have larger pressure drop of liquid flow. We had a way to reduce the pressure drop of liquid flow by thickening the sintered copper powder, however, if the sintered copper powder was thickened when keeping the diameter of the heat pipe at the same size, the internal vapor space was reduced, and the vapor flow pressure drop was increased. Therefore, no proper countermeasures were found.

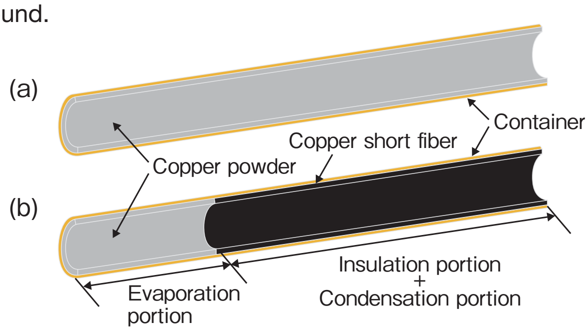


Figure 2 **(a) Structure of a conventional heat pipe.**
(b) Structure of a newly developed heat pipe (sintered copper powder + sintered copper short fiber).

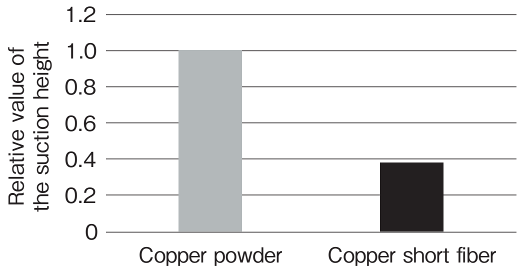
3. INTERNAL STRUCTURE OF A HEAP PIPE FOR THE TOP HEAT

The internal structure of the heat pipe is shown in Figure 2 (b), which was just developed to improve the heat transfer rate under the top heat condition. A combination of two kinds of sintered bodies was applied in the longitudinal direction. The sintered copper powder body which was conventionally in use was installed at the evaporation portion and the copper short fiber sintered body was installed at the insulation portion through the condensation portion. Because a higher capillary pressure was necessary to overcome the body force pressure drop caused by gravity, the copper powder which was conventionally in use was adopted to the evaporation portion. On the other hand, in the range from the insulation portion to the condensation portion, the influence of a pressure drop caused by the liquid flow was larger than the capillary pressure. Adopting the copper short fiber which had a higher transmission factor, we were able to reduce the liquid flow pressure, and as a result we found the heat transfer rate improved.

4. RESEARCH FOR THE WICK STRUCTURE

4.1 The Performance of a Wick for Sucking up the Liquid and the Expected Structure of the Wick

We prepared samples of heat pipes with the sintered copper powder and the sintered copper short fiber, each of which was different in its position and length to check any changes in the performance of sucking up the liquid in accordance with the wick structure. The suction height of the liquid at room temperature is shown in Figure 3 for the sintered copper powder and the sintered copper short fiber. The sintered copper powder was more effective for the higher suction height of the liquid than the one of the sintered copper short fibers. Because the capillary pressure is proportional to the suction height, the performance of such a structure was expected to be improved that sucks up the fluid through the sintered copper powder which had a larger capillary pressure after sucking up the fluid through the sintered copper short fiber which had a smaller liquid flow pressure drop. For reference, we also prepared samples which had the sintered copper short fiber at the evaporation portion.



$$\Delta P_c = \frac{2\delta\cos\theta}{\gamma_c} = \rho_l gh = \rho_l ghave$$

ΔP_c: Capillary pressure (Pa), h: Suction height (m),
$have$: Average suction height (m), ρ_l: Density of pure water (kg/m^3)
σ : Surface tension (N/m), θ : Contact angle (rad)
γ_c: Diameter of a pore (m), g: Gravitational acceleration (m/s^2)

Figure 3 **The equation to calculate the suction height and the capillary force of a wick.**
The suction height with the sintered copper powder is set at 1.0.

4.2 The Preparation of Heat Pipes to Examine the Wick Configuration

We installed a sintered body made of a copper powder and that of a copper short fiber in a copper pipe of ϕ8 mm in outer diameter and 200 mm in full length to make the structure shown in Figure 4 (a). Injecting water as a working fluid, heat pipe samples for our examination were prepared. We specified a sample with the sintered copper powder over its full length as (1) shown in Figure 4 (a), and that with the sintered copper short fiber over its full length as (6). And because the combination of the sintered copper powder and the sintered copper short fiber, which sucked the liquid through the copper short fiber first and the copper powder next was expected to improve the performance further, we specified samples as (2) and (3), and those which sucked the liquid through the sintered copper powder first and the sintered copper short fiber next as (4) and (5) for your reference.

4.3 The Measurement Condition of Heat Pipes to Examine the Wick Configuration

Applying grease to the surface of the evaporation portion of a heat pipe, we installed it on a heater block of 40 mm in length made of copper. Non-working portion of the heat pipe at the evaporation portion was 15 mm in length. The heater block was heated through a thermal contact with a cartridge heater through grease. And the condensation portion was installed on a cooling block of 100 mm in length made of aluminum after applying grease on the surface of the heat pipe. The non-working portion of the heat pipe at the condensation portion was 15 mm in length same as that at the evaporation portion. The cooling block was cooled through a thermal contact with a water-cooling jacket made of copper through grease. The sample was positioned as the top heat position shown in Figure 4 (b) and its verticality was checked with an angle meter. The measurement was carried out at the fixed working temperature of 50°C. The maximum heat transfer rate was measured as the value of the entering heat quantity just before the thermal resistance sharply increased, which was calculated from the difference of temperature between the heater block and the insulation portion of heat pipe.

4.4 The Measurement Results of Heat Pipes Samples to Examine the Wick Configuration

The measurement results of each heat pipe are shown in Table 1. In comparison to the heat pipe (1) with the sintered copper powder in its full length or that (6) with the sintered copper short fiber in its full length against those with the sintered copper powder + the sintered copper short fiber, we have found that (2) and (3) which were applied with the sintered copper powder over the evaporation portion had improved the heat transfer rate but (4) and (5) which were applied with the sintered copper short fiber over the evaporation portion had reduced the heat

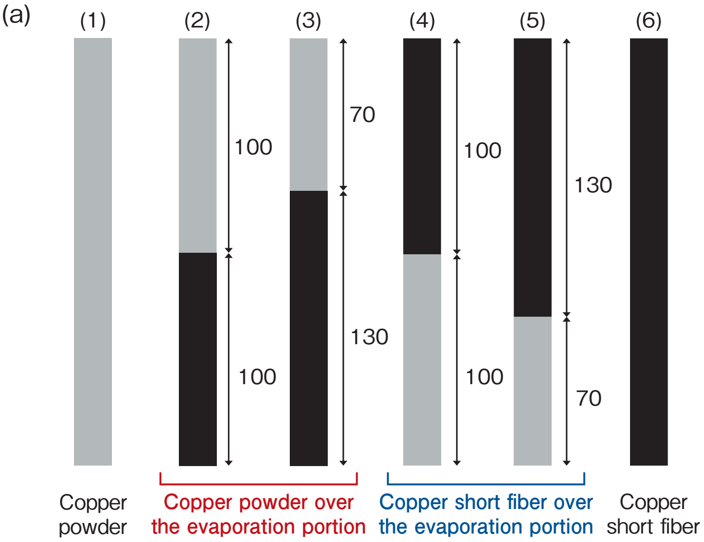


Figure 4 (a) The structure of heat pipes to examine the wick configuration.

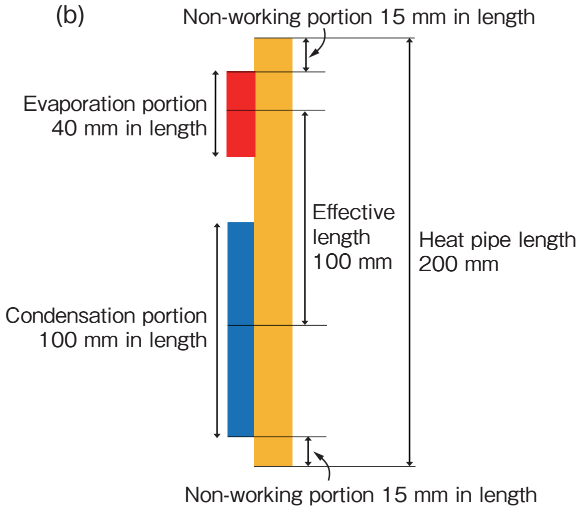


Figure 4 (b) The measuring condition of heat pipes.

Table 1 The experimental result of maximum heat transfer rate of heat pipes (200 mm in full length) in which the wick proportion was varied.
The maximum heat transfer rate of theoretical value is set as 1.0 when covering the full length of wick with the sintered copper powder ((1)).

		(1)	(2)	(3)	(4)	(5)	(6)
Relative values of maximum heat transfer rate	Experimental values	1.4	2.0	2.8	0.7	0.9	1.4
	Theoretical values	1.0	1.7	2.3	0.3	0.4	1.1
Wick configuration		Copper powder	Copper powder + Copper short fiber (Copper powder over the evaporation portion)		Copper powder + Copper short fiber (Copper short fiber over the evaporation portion)		Copper short fiber

transfer rate. Considering (2) and (3), the performance was improved because the liquid flow was sucked up through the sintered copper powder with a large capillary pressure after being sucked up through the sintered copper short fiber with a small liquid flow pressure drop as we had expected. Considering (4) and (5), we estimated that the performance became worse as a result of the insufficient capillary pressure of the sintered copper short fiber.

And, as for the sintered copper powder + the sintered copper short fiber, either (3) or (5) which had a lower proportion in length of the sintered copper powder (a higher proportion of the sintered copper short fiber), as a result showed a larger heat transfer rate than either (2) or (4) respectively. We estimated that it was caused by the effect of the lower liquid flow pressure drop reduced by an increased proportion of the sintered copper short fiber which had a larger transmission factor. It was confirmed that the value of the maximum heat transfer rate corresponded to the value estimated from theoretical calculations overall. That of either (4) or (5), which had the evaporation portion covered with the sintered copper short fiber, was found to deviate from the theoretical value. We estimated that the actual value of the heat transfer rate was found to be larger than the theoretical value because only the capillary pressure of the sintered copper short fiber was used in the calculation but actually not only the capillary pressure from the sintered copper short fiber but also that from the sintered copper powder, worked.

5. EXAMINATION FOR THE OPTIMUM SOLUTION OF THE WICK CONFIGURATION

5.1 Preparation of Heat Pipe Samples to Examine the Optimum Solution of the Wick Configuration

According to the measurement results shown in Chapter 4, we have found that such a structure was effective to improve the performance under the top heat condition that the evaporation portion was covered with the sintered copper powder and the condensation portion was covered with the sintered copper short fiber. So, we have examined the optimum proportion of the sintered copper powder and the sintered copper short fiber based on the structure in which the evaporation portion was covered with the sintered copper powder.

When maintaining the capillary pressure through the sintered copper powder at the level free from any problems, a longer sintered copper short fiber was preferable to improve the heat transfer rate by the reduction of flow pressure drop. On the other hand, there was a possibility that the liquid was not able to return to the position of the sintered copper powder, when the sintered copper short fiber was too long, because the height from the bottom, to which the liquid can reflux through the sintered body was determined according to the capillary pressure. Then, the length with which the sintered copper short fiber was able to reflux the liquid when the heat pipe was positioned at the top heat position (45 degree) was set as a standard (the sintered copper short fiber 300 mm, (9) shown in Figure 5 (a)). In order to check the change of performance caused by the change of proportion in length of the sintered copper powder against the sintered copper short fiber, we prepared samples respectively for each side of the proportion standard ((8) and (10)) as well. Specifically, we installed the sintered copper powder and the sintered copper short fiber respectively in a copper pipe of $\phi 8$ mm in outer diameter and 400 mm in full length in a configuration such as shown in Figure 5. Injecting water as a working fluid, heat pipe samples for our examination were prepared. Further, we prepared such a heat pipe that had only the copper powder sintered over its longitudinal full length to check improvements by applying the sintered copper short fiber ((7)).

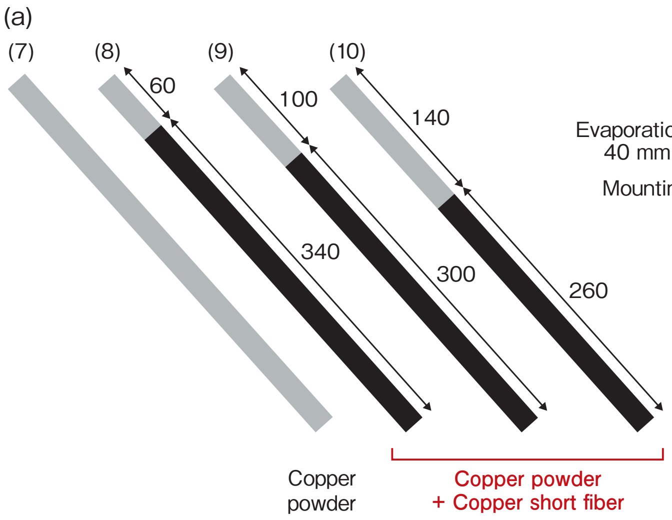


Figure 5 (a) The structure of a heat pipe to examine the optimum wick configuration.

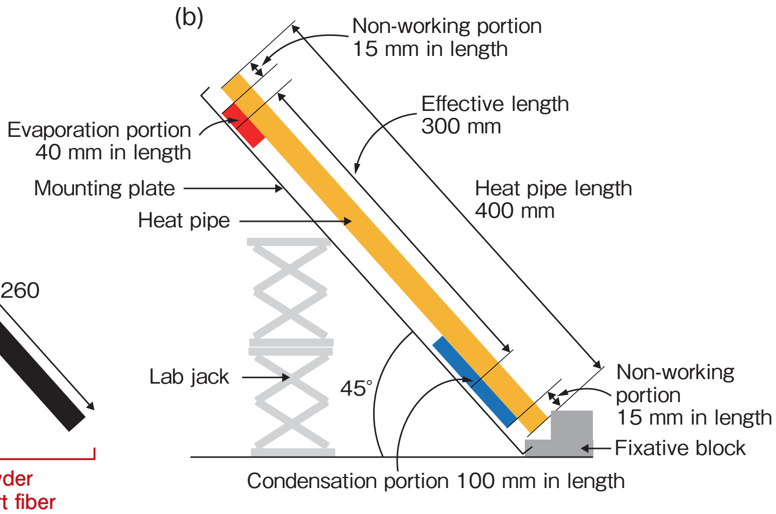


Figure 5 (b) The measuring condition of heat pipes.

5.2 The Measurement Condition of Heat Pipe Samples to Examine the Optimum Solution of the Wick Configuration

How to provide the angle for the top heat position is explained as follows. A set of a heat pipe and a block were placed on a plate and fixed to secure its stable position and to provide more efficient handling. As shown in Figure 5 (b), the evaporation portion was positioned at the top side of the heat pipe, and it was tilted to the position at an angle of 45 degree. The tilt angle was adjusted by changing the height with a lab-jack placed under the mounting plate. The total structure was fixed by placing a metal block at the condensation portion.

Other measurement conditions were same as those shown in Clause 4.2.

5.3 The Measured Results of Heat Pipe Samples to Examine the Optimum Solution of the Wick Configuration

The measured results were shown in Figure 6. As a result, any of the heat pipes ((8), (9) and (10)) which had the wick made of the sintered copper powder + the sintered copper short fiber, had a better heat transfer rate in the top heat condition by approximately two times than the heat pipe which had the wick made of the sintered copper powder only over its full length. We estimated that the liquid flow pressure drop was reduced with the effect of increased length of the sintered copper short fiber, which had a larger transmission factor similar to the examination result of Clause 4.3. Considering the effect of the proportion of the sintered copper powder and the sintered copper short fiber to the performance, the heat transfer rate was more improved as the length of the sintered copper powder became shorter based on the calculations, however, as an actual result, the performance remained at the same level independently from the proportion. In comparison against the results of (2) and (3) in Clause 4.3, where the experimental values had agreed with the calculation values, we estimated it was because the changed proportion of the length of the sintered copper powder against the full length was smaller.

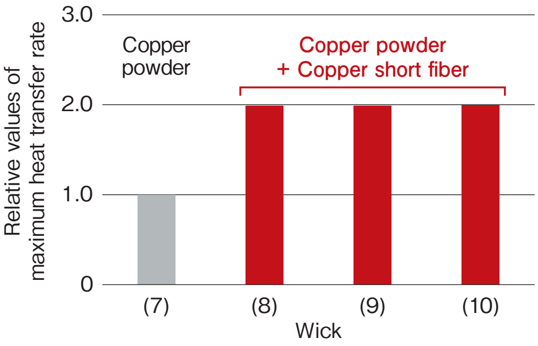


Figure 6 **The experimental result of maximum heat transfer rate of heat pipes in which the wick proportion was varied. The maximum heat transfer rate of theoretical value is set as 1.0 when covering the full length of the wick with the sintered copper powder ((7)).**

6. CONCLUSION

We have found that the heat transfer rate in the top heat condition was improved when we installed the sintered copper powder with a high capillary pressure at the evaporation portion and the sintered copper short fiber with a small liquid flow pressure drop both at the insulation portion and at the condensation portion.

In response to increasing development of electronic devices, we are going to improve the performance of heat pipes and heat pipe heatsinks further and continue to contribute to the development of electronic devices.

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