Ultra Thin Flat Heat Pipes

for Thermal Management of Electronics

Introduction

The decrease in size of the new generation of portable electronic devices imposes a severe constraint on their incorporated thermal management devices. Thinner and more compact laptops, for instance, require ultra thin form factor cooling devices. For example, newly developed mobile processors in BGA packages must be thin enough for use in notebooks only 18 mm thick [1]. Traditionally, flat heat pipes have been used for this type of application.

However, the smaller form factor comes with a heat transfer capacity penalty. Figure 1 [2] shows an example of such decrease for a common heat pipe employing a grooved wick. Naturally, a heat pipe has a maximum heat transfer capacity when its cross section is round. As the device is flattened, its heat transport capacity decreases. As illustrated below, if the thickness is reduced from 6mm (round) to 2 mm (flat), the maximum heat transport capacity drops from over 100 W to less than 20 W. If we further flatten the device, the cooling capacity becomes even lower (less than 10 W). Obviously, such a thermal management device, while complying from a form factor standpoint, will not serve its functional purpose.

To overcome this problem, Hirofumi et al [2] built ultra thin heat pipes using a special wick structure. The ultra thin heat pipes were made of regular copper pipe 6 mm in diameter, flattened down to

two thicknesses: 1 mm and 0.7 mm. The length of the 1 mm and 0.7 mm heat pipes is 150 mm and 100 mm, respectively. Both devices are 9 mm wide.
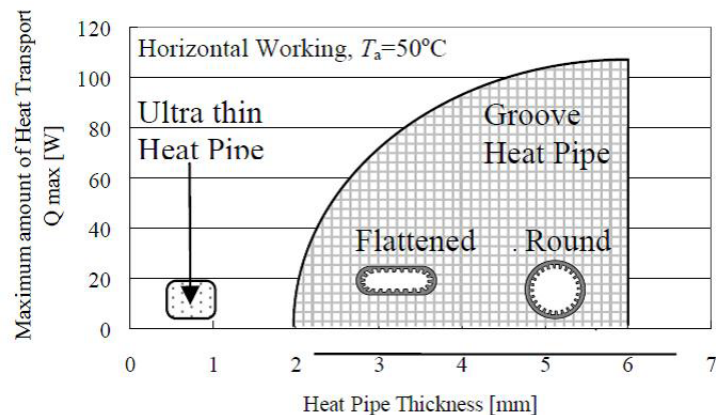

Figure 1. Maximum Heat Transfer Capacity Dependence of Heat Pipe Thickness [2]
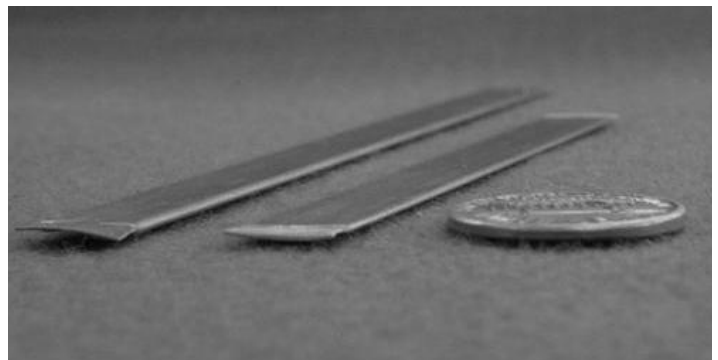

Figure 2. Hirofumi Ultra Thin Heat Pipes [2]

Background

Before addressing the specifics of the above ultra thin heat pipes, let us revisit some basic background information about heat pipes. A heat pipe is a sealed vessel (usually made of copper), incorporating a small amount of working fluid, usually water. It has three sections: evaporation section (working liquid turns into vapor here), adiabatic section and condensation section (where vapor reverses to the liquid phase). In order for the device to function, the condensate must return to the evaporator in a timely manner. This function is served by a wick structure that must be placed on the walls of the enclosure. The wick enables the liquid return from the condensation section to the evaporator through capillary action. The three most common types of wick structures are: metal sintered powder wick, grooved wick and metal mesh wick. If the liquid does not return to the evaporator, a so called "dry out" condition occurs and the heat pipe ceases to function properly.

In order for a heat pipe to operate, the following condition must be satisfied:

$$\Delta P_c \geq \Delta P_v + \Delta P_l$$

where,

ΔP_c = capillary pressure (Pa)

ΔP_v = pressure drop of vapor flow (Pa)

ΔP_l = pressure drop of liquid flow (Pa)

So, the capillary pressure provided by the wick must overcome the pressure drops due to vapor and liquid flows. The capillary pressure can be expressed as:

$$\Delta P_c = \frac{2\sigma}{r_c} \cos\theta$$

where,

σ = surface tension of working liquid (N/m)

r_c = effective pore radius of the wick (m)

θ = mesh wallworking liquid contact angle (degrees)

The pressure drop due to liquid flow through the wick is given by:

$$\Delta P_l = \frac{\mu_l Q L_{eff}}{K A \rho_l \lambda}$$

where,

μ_l = viscosity of the working liquid (Pa•s)

L_{eff} = effective length (m)

K = permeability of the wick (m²)

A = wick cross-sectional area (m²)

ρ_l = density of the working liquid (kg/m³)

λ_l = latent heat of vaporization of the working fluid (J/Kg)

Table 1 summarizes typical values for the most common used types of wicks.

category	Effective Pore radius [m $\times 10^{-3}$]	Permeability [m² $\times 10^{-10}$]
100mesh	0.12	1.8
Sinter	0.01-0.1	0.1-10
Groove	0.25-1.5	35-1250

Table 1. Characteristics for Three Commonly Used Wick Structures [2]

Clearly, the sintered powder wick offers flexibility in the choice of effective pore radius (a small radius yields high capillary pressure, according to the equation (2) However, decreasing the pore radius will have an adverse effect on the permeability, hence increasing the pressure drop due to the liquid flow equation (3). So, an optimum must be sought.

Ultra Thin Heat Pipes Thermal Performance in Horizontal Position

Back to the ultra thin flat heat pipe case, a typical grooved wick will not be appropriate, since by the flattening process the vapor space inside the pipe will narrow, leading to high velocity vapor flow and hence high ΔP_v. Instead, the authors devised the mesh wick placement depicted in Figure 3.
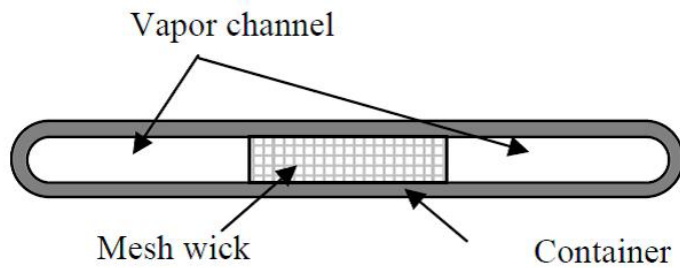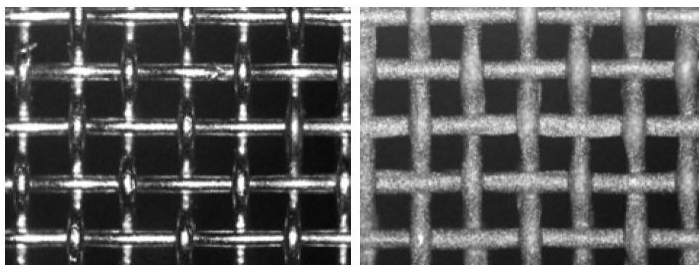
Figure 3. Structure of the Ultra Thin Heat Pipe [2]

Figure 5. Experimental Setup [2]

In order to increase ΔP_c, a special copper mesh has been used. This type of mesh provides a higher capillary pressure than the grooved one. An alternative would have been a sintered powder wick, since it also has a high capillary pressure. However, this option was eliminated due to a high ΔP_l associated with it. To further increase the capillary pressure, the wick was subjected to an oxidation-reduction process (Figure 4 (b)). As a result, the surface of the mesh wire has roughened and the wire diameter has increased. This improves the wetting of copper by the working liquid (water), which leads to a higher ΔP_c (equation (2)).

(a) Reduction only   (b) Oxidation-reduction

Figure 4. Copper Mesh Used for Ultra Thin Heat Pipes [2]

The thermal performance of the heat pipes was tested using the experimental set up illustrated in Figure 5. The adiabatic section was kept at constant temperature (50°C). The thermal performance tests were performed with the heat pipes in horizontal position. Several K-type thermocouples were placed along the heat pipe. The thermocouple location is presented in Figure 6.
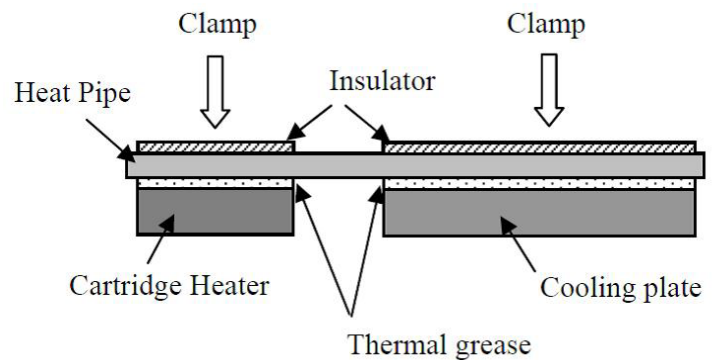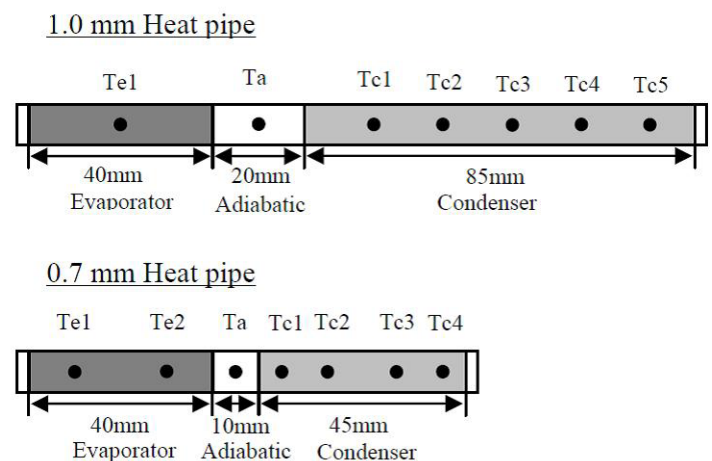

Figure 6. Thermocouples Location for 1 mm and 0.7 mm Thick Heat Pipes [2]

In order to quantify the thermal performance, the following thermal resistances are defined for the heat pipe:

a) Thermal resistance of the evaporator (°C/W):

$$R_{e-a} = \frac{(T_e - T_a)}{Q_{in}}$$

where,

T_e = temperature of the evaporation section (°C)

T_a = temperature of the adiabatic section (°C)

Q_{in} = heat load (W)

b) Thermal resistance of the heat pipe (also called thermal resistance of the evaporator to condenser) (°C/W):

$$R_{e-c} = R_{hp} = \frac{(T_e - T_c)}{Q_{in}}$$

where,
T_c = temperature of the condenser section (°C)

As mentioned before, the dry out condition must be avoided for a proper heat pipe operation. During testing, the dry out condition is indicated by a sudden jump in R_{e-a}. Therefore, the maximum heat transfer capacity of a heat pipe is defined as the heat load prior to the thermal resistance jump.

Experimental results for the 1 mm thick heat pipe are presented in Figure 7. The test was performed for three types of wick structures. The copper mesh wick subjected to oxidation reduction is clearly superior, producing the lowest thermal resistance and the maximum heat transfer capacity of 20 W.
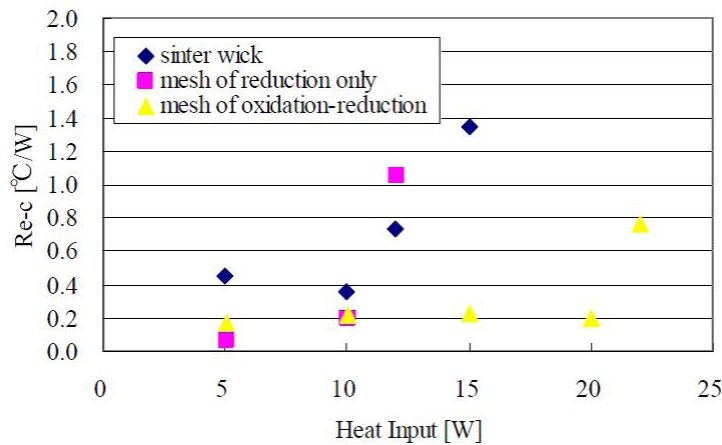

Figure 7. Thermal Resistance vs. Heat Input for 1 mm Thick Heat Pipe, with Different Wick Structures [2]

The 0.7 mm thick heat pipe yielded a worse thermal performance than its thicker counterpart as shown in Figure 8. The thermal resistance is about 0.4 °C/W and the dry out condition occurs at 8 W heat input.
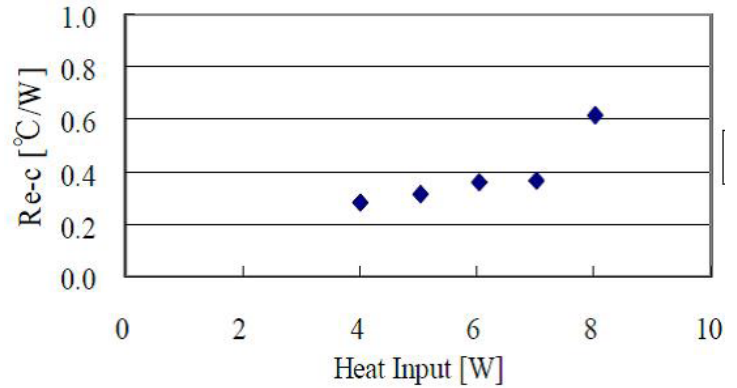

Figure 8. Thermal Resistance vs. Heat Input for 0.7 mm Thick Heat Pipe [2]

This decrease in thermal performance is explained by the reduced inner space for vapor flow. The increase in vapor pressure drop ΔP_v cannot be compensated for by the increased ΔP_c anymore, since the mesh wick cannot function properly in such a reduced height configuration.

Cooler Master is also proposing slim heat pipes [2]. Their pipes are bendable and can be as thin as 1 mm (Figure 9).
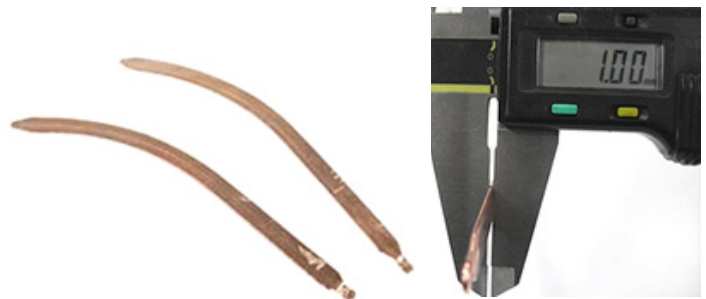

Figure 9. Cooler Master Slim Heat Pipes [1]

Similar to [2], the slim heat pipes are made of regular 6 mm copper pipe with a length of 150 mm. The container material is copper and the working fluid is water. However, the wick structure is made of sintered metal powder. One of the Cooler Master's designs is presented in Figure 10. As can be seen, the wick only partly lines the inner wall of the heat pipe, allowing for more of a cross section for the vapor flow.
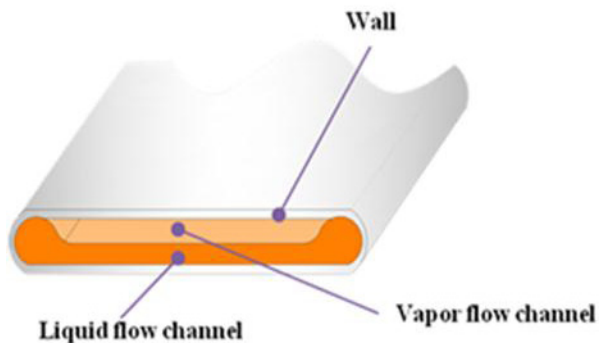
Figure 10. Heat Pipe Cross Section [1]

The thermal performance of slim heat pipes with the above cross section is presented in Figure 11. The thermal resistance is very low (0.1 °C/W), up to 20 W heat input. For heat loads in excess of 20 W, the heat pipe thermal resistance increases gradually.
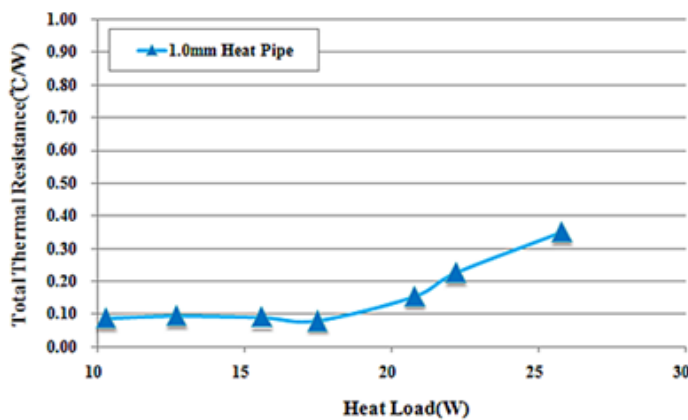

Figure 11. Thermal Performance of Cooler Master's Slim Heat Pipes [1]

Ultra Thin Heat Pipes Thermal Performance at Various Tilt Angles

The thermal performance tests mentioned so far were performed with the heat pipes operating in a horizontal position. Of course, it is of utmost interest to know the functionality of heat pipes under tilt angles. In this experiment conducted by Hirotumi [2], the evaporation sections of the heat

pipes were inclined from horizontal up to 90°. The graphs in Figure 12 present such a performance for the two thicknesses studied. Generally speaking, when operating against gravity (the evaporation section placed above the condensation section), the maximum heat transfer capacity decreases and thermal resistance increases. That is due to the fact that the condensate (liquid) has to return to the evaporator section against gravity. For instance, for the 1 mm thick heat pipe, the maximum heat capacity decreases to 10 W from 20 W in a horizontal position.
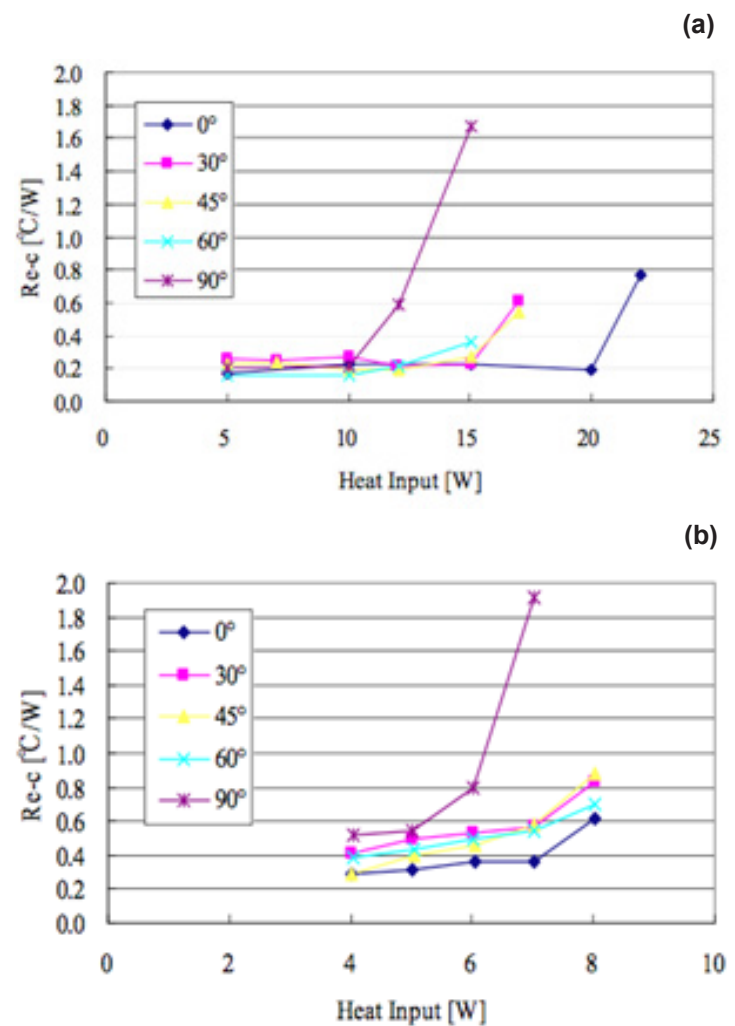
(a)

(b)

Figure 12. Thermal Performance Under Tilted Condition [2] (A) 1 mm Thick Heat Pipe and (B) 0.7 mm Thick Heat Pipe

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Conclusions

In conclusion, ultra thin heat pipes capable of responding to the size and cooling demands of the new generation of mobile electronic devices have been successfully developed. By carefully choosing the mesh type and size, maximum heat transfer capacities in excess of 20 W and thermal resistances as low as 0.1 ºC/W have been attained. The thinnest heat pipe (0.7 mm) has a maximum heat transfer capacity of 7 W and a thermal resistance of 0.4 ºC/W. In addition, these heat pipes function reasonably well under anti-gravity conditions.

References:

1. http://odm.coolermaster.com/solution. php, Cooler Master 2013.

2. Hirofumi, A., et al., "Development of Ultra Thin Plate-Type Heat Pipe with Less Than 1 mm Thickness", 26th IEEE SEMI-THERM Symposium, 2010.