A Heat Sink

with an Integrated Heat Pipe

An interesting heat sink was built recently by researchers seeking to create a cooling solution for high-power applications [1]. The researchers' approach was to use heat pipe technology, but apply it in a radically different way, in order to optimize performance and minimize weight and size. Heat pipes and vapor chambers have been used to effectively cool high-powered electronics because they can have conductivities 10 times that of copper or even higher. Hence, heat pipes and vapor chambers are able to move heat from a component that may be small and have very high heat flux density to a remote heat sink with large surface area where the heat is rejected to ambient air.

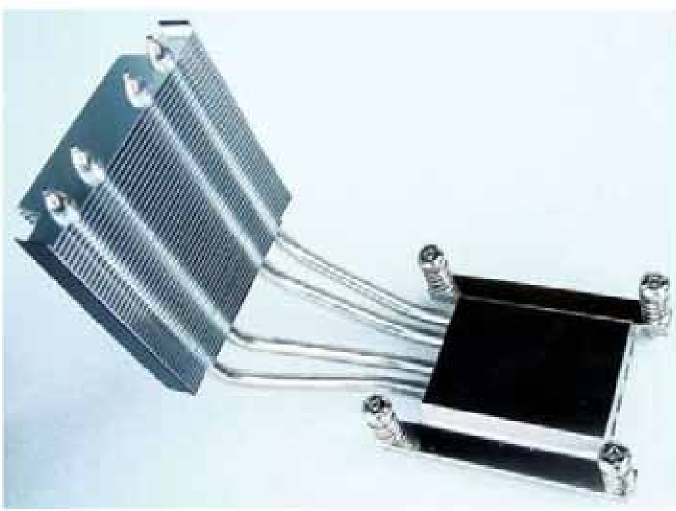

Figure 1 - Typical Heat Pipe-Heat Sink Assembly [2]

In a heat pipe or vapor chamber, there are three operating sections: evaporator, adiabatic and condenser (See Figure 2 below). In the evaporator section, the heat source causes a fluid (commonly water) to evaporate. This vapor travels through the adiabatic section and returns to liquid phase in the condenser, where the heat travels out of the heat pipe to the heat sink. The liquid then returns to the evaporator along the walls of the heat pipe, moving by capillary action along some sort of wick structure.

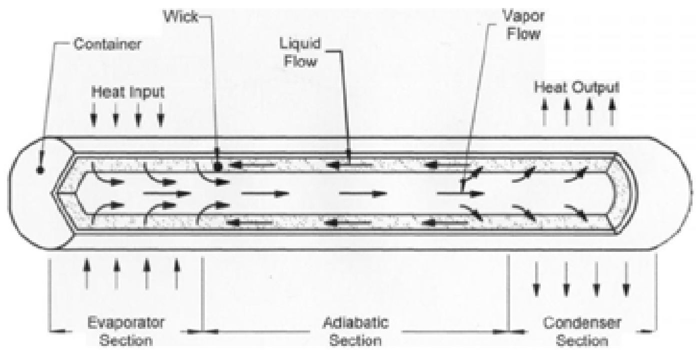

Figure 2 - Heat Pipe Diagram [3]

It can be seen in Figure 1 that for a heat pipe-heat sink, there are interfacial resistances between the component and the heat spreader, between the heat spreader and the heat pipe, and also between the heat pipe and the cooling surfaces. The experimental heat sink with an integrated heat pipe, constructed by Xie et al, does away with many of these resistances by turning the base of the heat sink into an evaporator chamber, seen in Figure 3 - Heat Sink with Integrated Heat Pipe [1] below. The vapor generated in the base then travels within three broad, flat channels which form the evaporator sections. These broad, flat sections were then brazed to fins 0.08mm thick. The total surface area of the cooling fins was about 0.4 m^2, and all parts of the heat sink were made from copper.

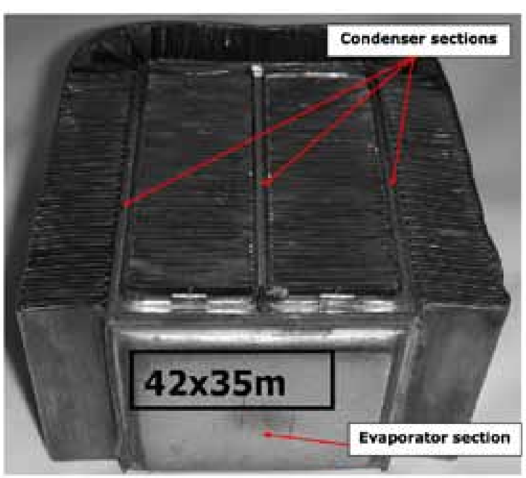

Figure 3 - Heat Sink with Integrated Heat Pipe [1]

The evaporator and condenser sections make up the body of the heat sink, and they are made from stacked plates, shown in Figure 4. The edges of the many plates are what form the wicking structure for the heat pipe, returning the condensate to the evaporator. It can be seen here that the condenser surface area for this heat sink is much larger than the area that would be found in one, or even several, heat pipes. The folded fin construction also provides a relatively large surface area for heat transfer from the condenser to the fin. Overall, the heat sink measures 88 x 80 X 46 mm in height, width and length.

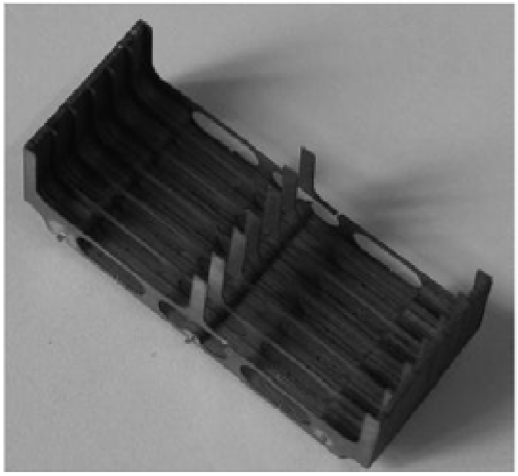

Figure 4 – Internal Structure of the Heat Pipe-Heat Sink [1]

Heat sinks with vapor chambers embedded in the base are on the market currently, but they only spread heat along the plane of the component. There is then an interface resistance between the vapor chamber and the heat sink, after which there is a spreading resistance along the heat sink itself. One such example is from Thermacore, Inc., and can be seen in Figure 5. It can be seen that the vapor chamber spreads heat horizontally, after which it is conducted along the fins. Heat sinks incorporating vertical heat pipes distribute the heat away from the component, but then they are limited by their condenser surface area [1].

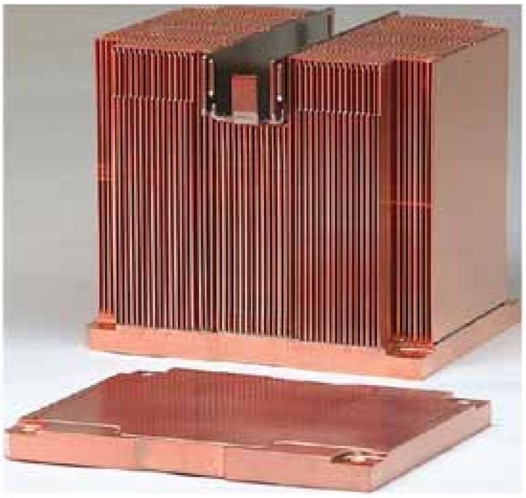

Figure 5 - Therma-Base™ Technology from Thermacore [4]

The experimental heat sink is certainly more complicated and would cost more to produce, but does it have performance advantages? The fact that water vapor is allowed to travel up through the body of the heat sink should be a great performance benefit. In simulations of heat pipes, water vapor has been modeled with equivalent thermal conductivity of 30,000 W/m-K, compared to about 400 for pure copper [5].

In order to measure the performance of the heat pipe-heat sink, Xie et al. placed the heat sink in a duct, where all measured air flowed through the heat sink. Power was applied to a heater embedded in a copper block, and thermal grease was applied between the block and the heat sink base. The heating unit and outside surfaces of the heat sink were then covered in insulating material. Thermocouples measured the temperature at the center of the heating block, at four points on the heat sink itself, and of the ambient air.

Power was applied to the heat sink in increments of 50 W, and temperatures were reported when the system reached steady-state. This procedure was repeated for four different airflow velocities, which ranged from approximately 0.8 to 2.9 m/s. Temperatures were reported in terms of the difference between the center of the heater block (which is the maximum temperature in the system) and the ambient air. The relationship between ΔT and power applied was nearly linear, as seen in Figure 6. This is explained by the fact that the major resistance in the system was convection heat transfer from the fins to the air, and this resistance only varied with the air speed. So as more power was applied, then the temperature gradient had to increase as well to increase the amount of heat transfer.

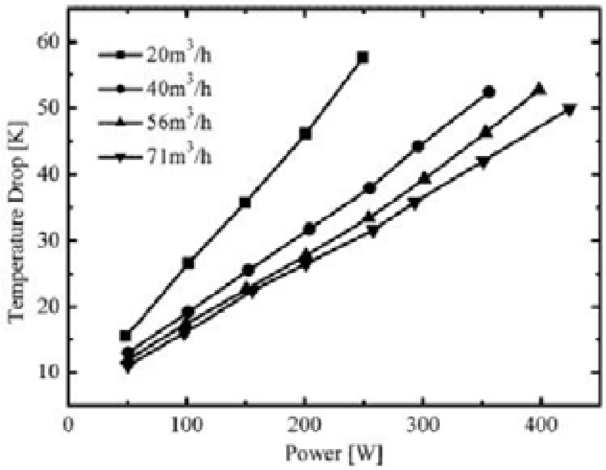

Figure 6 – Temperature vs. Applied Power at Different Flow Rates [1]

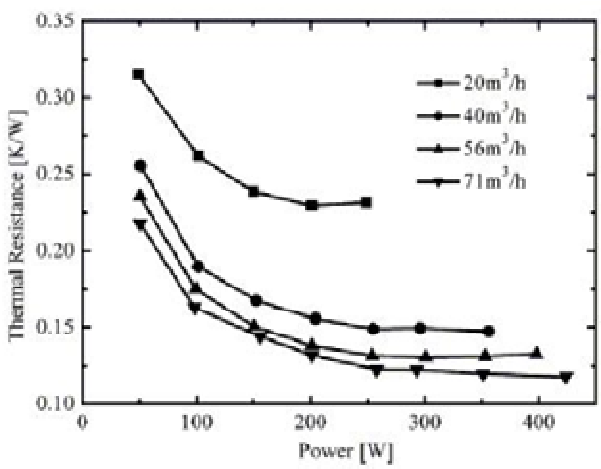

Figure 7 – Thermal Resistance vs. Applied Power [1]

However, when we examine the thermal resistance vs. power in Figure 7, the relationship is clearly not constant, which seems to go against expectations. Thermal resistance is calculated from Equation 1 below, and seems like it should not change for a given amount of airflow. In this instance, the observed behavior is explained by the fact that the ΔT is measured from the hottest point of the heater, and does not reflect the average temperature across the entire base of the heater and heat sink. At low power levels, coolant only vaporized over a small central portion of the evaporator. At higher power levels, the entire evaporator surface was used to vaporize coolant, so at a certain power level, the calculated resistance becomes fairly constant as expected.

$$R = \frac{T_{heater} - T_{ambient}}{\dot{Q}} \qquad (1)$$

That the heat sink is not fully utilized until faced with higher power dissipation can also be seen in the temperature distribution along the condenser surface. Thermocouples were placed on the wall of the condenser on the air inlet side. TC1 and TC2 were placed at the bottom, near the evaporator, and TC3 and TC4 were placed near the top of the heat sink. It can be seen in Figure 8 that the top of the condenser is not being used when applied power is low, and condensation is occurring on the surfaces close to the evaporator. When applied power reaches 150W, the condenser temperature becomes uniform as the entire surface is utilized.

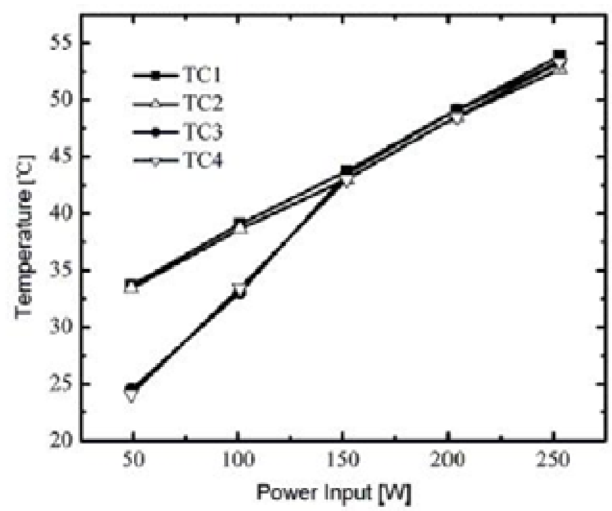

Figure 8 – Condenser Temperature vs. Applied Power [1]

The heat sink was tested at a maximum of 420W, where the ΔT was 50ºC, and the thermal resistance was 0.118 ºC/W. The air velocity at that point was 2.9 m/s, and the pressure drop was measured to be 30 Pa, which is normal for the fairly tight fin pitch. Of note is the fact that the thermal resistance remains around 0.16 ºC/W at a much lower airflow rate.

A search of the web turns up a number of commercial

CPU coolers using heat pipes that boast similar thermal resistances, but at an unlisted airflow rate [6,7]. As well, most CPU coolers are around 120 mm square with varying thickness, so they are quite a bit larger than the experimental heat pipe-heat sink tested by Xie et al. The performance of the experimental heat sink for its size is notable, and it would be interesting to see how the heat sink would perform with some fin optimization. Also, because the heat sink is made of stacked plates, the internal structure could be modified to observe the effect of different wick structures.

This heat sink design also suffers from high thermal resistance at low power levels. For example, at 100 W, which is around the power dissipation of many modern CPUs, the best thermal resistance is observed to be around 0.17 ºC/W. This is much higher than commercial heat pipe heat sink assemblies, which have been tested at 0.1 ºC/W, but the real advantage of this heat sink is its size. As mentioned before, the price for this kind of design would most likely be a disadvantage, but for high heat transfer in a small amount of space, it could be worth further research.

References:

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2. "New Heat Pipe Systems: Two New Mini-Powerhouses from Shuttle", http://www.tomshardware.com/reviews/mini,583-6.html, [Jan. 18, 2012].

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