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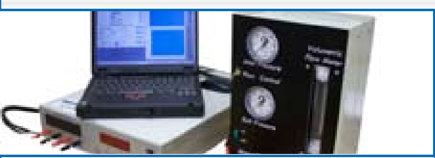
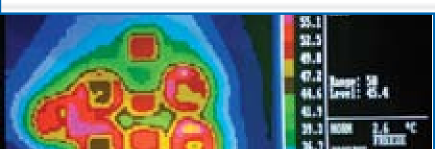
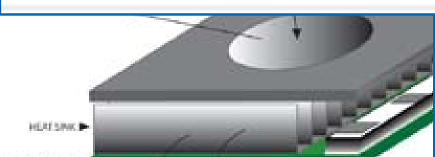
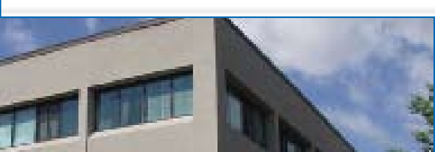








FUTURE COOLING

Experimental Study on a Hybrid Liquid/Air Cooling System

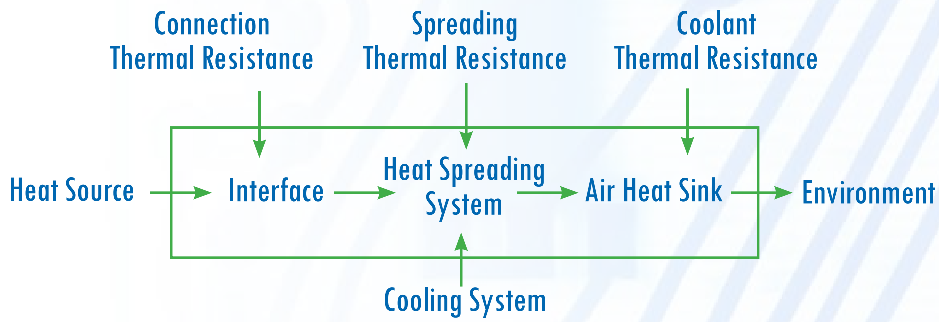


Figure 1. Typical Electronics Cooling System

As electronics become faster and more powerful, thermal solutions must evolve to deal with the increasing heat loads. Simply increasing the size of a heat sink, or adding a fan, was once enough to provide the required increased performance. But, while air cooling remains the dominant method of thermal management in the electronics industry, there are applications where traditional air cooling is not sufficient. These are bound to increase in frequency in the near future.

Today, liquid cooling is being used in a steadily increasing number of thermal applications. Desktops, servers, and even laptops are all potential products for such cooling methods. The attractiveness of liquid is its density and specific heat over air (Table 1). However, these material properties can be misleading if compared side by side.

In electronics, there is no basis for comparison between air and liquid for cooling. The term liquid cooling is itself misleading, as air is the final coolant in nearly all applications. The role of the liquid is not as a coolant, but as an active thermal transport vehicle. The main benefit from using liquid is the reduced thermal resistance from the heat source to the air cooled system peripheries. This is due to forced convection replacing pure conduction as the heat transport method, where the heat is delivered to the convective surfaces.

Table 1. Physical Properties of Air and Water [1].

Material	Density (kg/m3)	Specific Heat (kJ/kg-K)
Air	1060	1.2
Water	4186	998

In general, all electronics cooling systems can be divided into three important components as shown in Figure 1:

- Interface
- Heat spreading
- Ambient heat exchanger

The Interface refers to the junction between the component and heat sink or cold-plate. This resistance is typically minimized with a high performance grease or phase-change material, and is the same in both liquid and air cooling systems.

The spreading resistance in a thermal solution can be described as the transport of heat from the component to the cooling surfaces that are in contact with the ambient air. This is the only part of a cooling system that greatly differs from air to liquid cooling. With a typical air cooled heat sink, the thermal spreading is done at the base of the heat sink through pure conduction. When using liquid, the spreading is done by the movement of the liquid in a loop from the cold-plate to heat exchanger by mass transport, i.e. coolant.

The final part of an electronics cooling system is the ambient heat exchanger. For air cooling, this part is the heat sink fins, and for liquid cooling is the radiator fins. Both systems work in the same way, by using extended surfaces (fins) to transfer heat into the ambient air through convection.

Unless one is using a natural body of water for coolant, or operating in space, at the end of every cooling solution there is a liquid to air heat exchanger, when the generated heat is transferred.

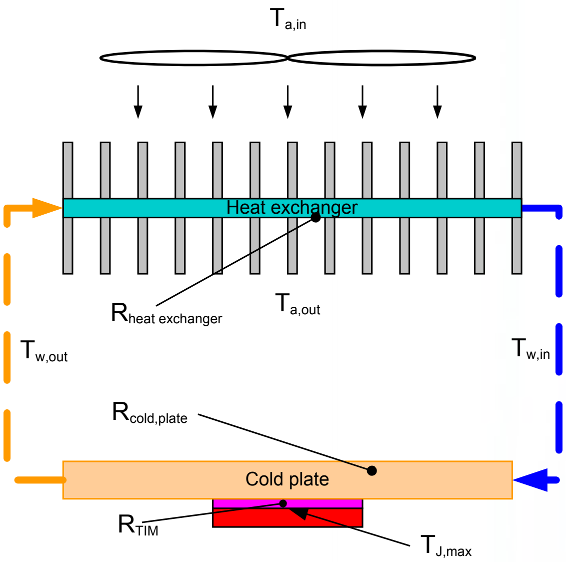


Figure 2. Typical Liquid Cooling System

As shown in Figure 2, a conventional liquid cooling system consists of a cold plate, external plumbing, and a heat exchanger. The advantage of this type of system is to increase flexibility in packaging by allowing remote placement of the heat exchanger. Remote mounting does introduce disadvantages, as the external plumbing increases pressure drop throughout the system, which increases the required pumping power. The piping itself is a potential source of leakage at the plumbed junctions, as is the permeability of the piping system.

To appreciate the importance of spreading resistance, let's assume a high heat flux component generates 500 W/cm^2 in a 10 x 10 mm package. The size of the copper heat sink used is 80 x 80 mm, with a base thickness of 5 mm. The spreading resistance alone for this case is 0.14 ^{o}C/W. Even if the thermal resistance of the heat sink is 0 (thermodynamically impossible), the temperature rise of the component above ambient is 70 ^{o}C. Concidering an ambient of 50 ^{o}C, the above proposed heat sink will not cool the device adequately to prevent it from failure. The above example shows how important the spreading resistance is,
especially in high heat flux applications.

There are many methods for reducing the thermal resistance. Among these methods are:

- Use of a high conductivity material as the base plate of the heat sink to reduce thermal resistance. These materials include aluminum (k = 180 W/mK), copper (k = 380 W/mK), and CVD diamond (k = 2000 W/mK).
- Using passive, high conductivity devices, like heat pipes, thermosyphons, or vapor chambers
- Use of thermoelectric devices whose heat spreader structures consist simply of an electrically conductive heat sink with an applied external electric potential. This induces a Thomson Effect, and provides heat transfer through the device.

Of the above, the vapor chamber has been the most desirable method. Basically, a vapor chamber works like a heat pipe. The heat transfer to the base vaporizes the liquid and reaches the cold section of the chamber. The vapor condenses and returns back to the base with the help of the wick structure. But, even though the spreading resistance of a vapor chamber is theoretically appealing, it has been found that, under certain conditions, a solid copper spreader can have lower thermal spreading resistance [2,3,4].

Figure 3 shows the comparison between a copper heat sink and a vapor chamber.

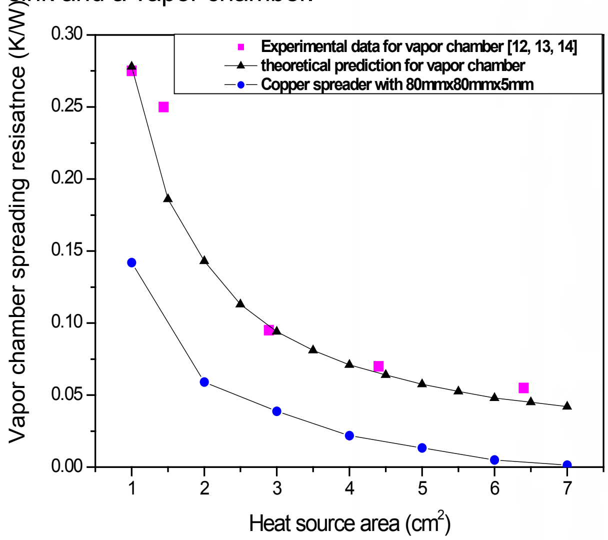
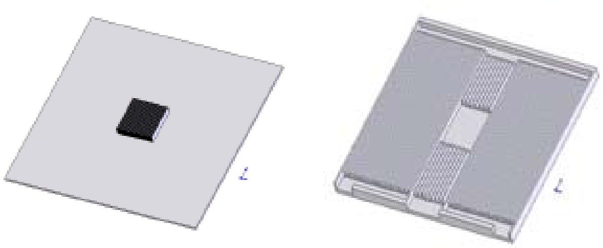


Figure 3. Comparison of a Solid Copper Heat Sink and a Vapor Chamber

In order to alleviate spreading resistance issues, Advanced Thermal Solutions, Inc. (ATS) has developed a new technology, the Forced Thermal Spreader, or FTS [5]. A schematic picture of the FTS design is shown in Figure 4.



(a) Top micro-channels (b) Bottom mini-channels

Figure 4. Structure of Advanced Thermal Solutions' Forced Thermal Spreader (FTS).

The FTS design is a combination of mini- and micro-channels. The heat transfer coefficient in the micro-channels is about 500,000 W/m ^{2o}C. This high heat transfer coefficient creates a very small resistance between the heat source and the incoming liquid. The heat is then transferred to the bottom of the heat sink with the mini-fins attached to the top plate. Heat then transfers from the top plate to the ambient through the heat sink. The experimental test set up is shown in figure 5.

An experiment with an FTS was performed using an HFC-100 test equipment developed by ATS. The HFC-100 is a computerized data acquisition system capable of controlling up to 1KW of heat generated on a 1 cm^2 simulated chip. This instrument is capable of ramping the heat with specified dwell times. The size of the FTS was 100 x 120 mm.

Table 1 shows the experimental data from tests performed at power levels of 100, 200, and 300 W/cm^2. The results show that the data is independent of the power. The experiment was conducted several times at each power level to ensure data repeatability.

Figure 5. FTS test set up.

Table 1. Experimental Data for the Thermal Resistance of the FTS.

Test Number	1	2	3	4	5	6
Power applied (W)	100	100	200	200	200	300
Water flow rate (L/min)	1.2	1.0	1.2	1.2	1.2	1.2
Total thermal resistance (°C/W)	0.2587	0.2770	0.2474	0.2583	0.2693	0.2585
Interfacial thermal resistance (°C/W)	0.125	0.125	0.125	0.125	0.125	0.125
				Estimation from best condition		
Net thermal (°C/W) resistance of FTS	0.1357	0.1520	0.1224	0.1353	0.1443	0.1335
				Average of all is 0.137 °C/W		

The thermal resistance from the FTS is around 0.137 °C/W on average. The water flow rate is set as 1.0~1.2 L/min, and it was observed that increasing the flow rate beyond 0.3 L/min had no noticeable change in temperature.

One very noticeable phenomenon is the interfacial resistance. Because the heat source is small, 1 cm^2, this resistance value is significant even under best contact conditions. It is expected that this number would be much higher in a real device application. For proof, a second experiment was carried out. In this experiment the heat source was made part of the FTS, which eliminated the spreading resistance.

Table 2 shows the data for this case. The thermal resistance of the FTS is about 0.14 to 0.15 °C/W.

Table 2. Experimental Data for the Thermal Resistance of the FTS, With No Interfacial Resistance

Running number	Heat input (Watts)	Water inlet temperature (°C)	Junction temperature (°C)	Thermal resistance (°C/W)
1	100	33.54	48.96	0.154
2	100	32.82	48.18	0.154
3	200	36.18	60.84	0.123
4	200	34.30	62.53	0.141
5	200	32.56	59.62	0.135
6	200	34.22	63.92	0.148
7	300	42.50	83.84	0.138
8	300	35.96	78.12	0.14

The importance of the above numbers manifests itself when calculating the spreading resistance. For a 100 x 120 mm base size copper heat sink, and a 10 x 10 mm heat source, the spreading resistance is about 0.12 °C/W. To achieve the total resistance of 0.14 °C/W with a copper heat sink, we need a heat sink resistance of 0.02 °C/W, which is not feasible using just air. To show this, we can look at the thermal resistance of a heat sink:

$$R = \frac{1}{\eta h A} + \frac{1}{2\dot{m}C_p}$$

Where C_p is the fluid heat capacitance, h is heat transfer coefficient, and $\dot{m}$ is the mass flow rate. Assuming a heat transfer coefficient of infinity (thermodynamically impossible),

$$R = \frac{1}{2\dot{m}C_p}$$

To reach a resistance of 0.02°C/W, a velocity of 25 m/sec is required for a heat sink that is 100 mm wide and 20 mm high. In a typical systems environment, the h value is about 100-200 W/m^2°C for very high speed flows. Assuming this heat sink has 65 fins at 1 mm spacing, the convective resistance will be around 0.02 °C/W, but with an enormous amount of pressure drop of about 20 kpa (80' H_2O). This is clearly an impractical situation.

The data presented in this article shows that an effective hybrid system (liquid-assisted air cooling) has enormous capability for high heat flux applications. However the reader should not forget that the interfacial thermal resistance will always exist unless the interface is eliminated by integrating the cooling and the package systems. Equally important is the reliability of the cooling loops, as well as active control of the device functionality should the cooling system fail.

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