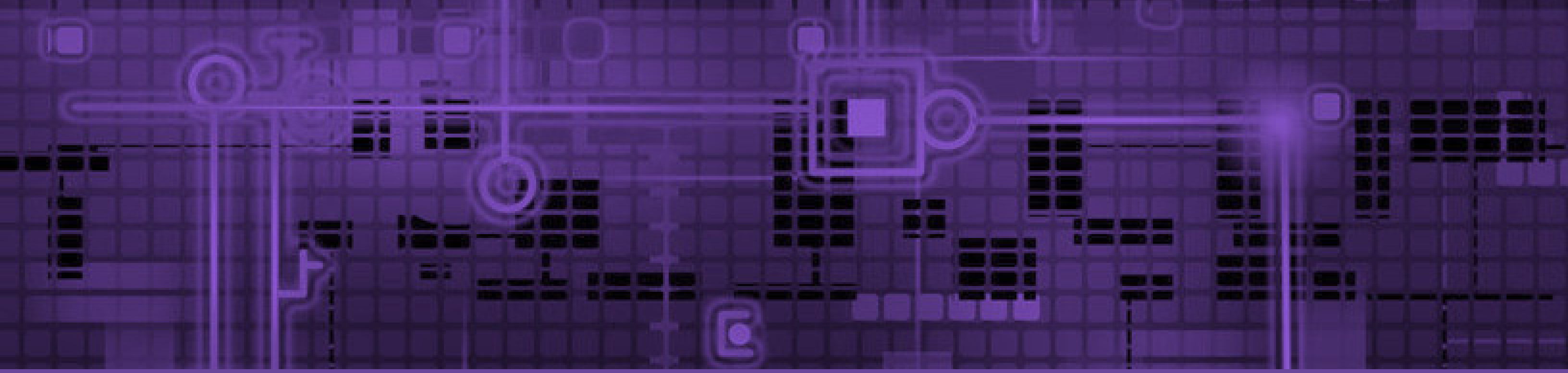

Advanced Cooling of Electronics

Using Liquid Metal as the Coolant

The increase of heat flux, shrinking footprint and decrease of available real estate on PCBs, adds to the complexity of managing heat and reducing the component temperatures for safe operation. In applications where air cooling is not adequate or not practical, liquid cooling can play a significant role. Liquid cooling can be achieved either using conventional pumps to run some sort of liquid, such as water/ethylene, or by utilizing liquid metal instead of conventional liquids. Using liquid metals has the advantage of employing an MFD (magneto fluid dynamic) pump with no moving parts, free of vibration. Plus, the high thermal conductivity of liquid metals makes them attractive for liquid cooling. Adding high thermal conductivity particles, such as aluminum or copper, to liquids named nanofluids has also been attempted. However, their use might be limited, due to fouling, particle deposition or conglomeration, degeneration of the solution quality and flow jamming over the channels [1].

Even though liquid metal cooling has been around for a long time, its use has been mostly in the field of nuclear reactors. Its employment in electronics cooling has been limited, due to its high price, toxicity and corrosive effects. Wilcoxon, et al [2] used liquid metal in developing a simple magnetic pump to transfer the heat from hot components. The simple schematic of their concept is shown in Figure 1.

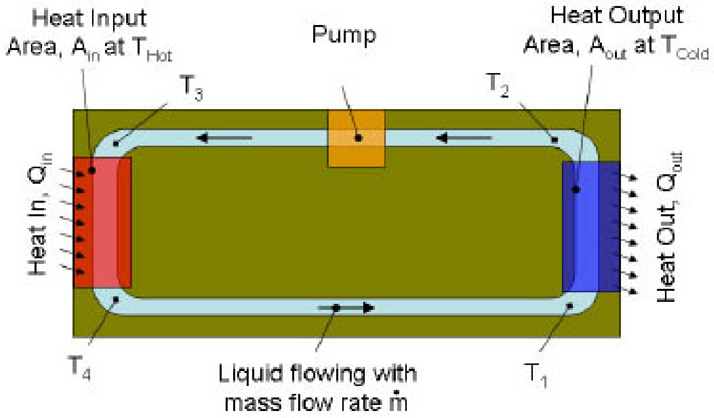

Figure 1. Schematic of Liquid Metal Loop [2]

Figure 1 shows that heat absorbed in the cold plate on the hot component is transported to the cold region. The cold section transports the heat to the ambient by either air or liquid means. The overall thermal resistance between the heat generating device and the heat rejection section can be represented as [3] neglecting interface resistance:

$$R = \frac{1}{\dot{m}C_p}\left(\frac{1}{\varepsilon_{hot}} + \frac{1}{\varepsilon_{cold}} - 1\right)$$

Where:

ε = heat exchanger effectiveness = $1-e^{NTU}$

$$NTU = \frac{hA_{eff}}{\dot{m}C_p}$$

h = heat transfer coefficient ($W/m^2 \cdot K$)

A_{eff} = effective heat transfer area on the hot and cold plates (m^2)

$\dot{m}$ = mass flow rate (Kg/s)

C_p - heat capacitance ($J/kg \cdot K$)

In effect, the thermal resistance is composed of convective heat transfer on both hot and cold surfaces and the capacitance thermal resistance of the fluid. Please note that the above thermal resistance does not include the resistance of the cooling mechanism, such as a heat sink or a heat exchanger. Since the heat has to be ultimately rejected to the ambient, the junction-to-air thermal resistance must include the extra thermal resistance of the heat sink/heat exchanger.

A plot of this equation as a function of ($\dot{m}C_p$) is shown in Figure 2. This equation clearly shows that, as the limit of the liquid capacitance becomes large, the resistance approaches $2/hA_{eff.}$ The smaller the $1/hA_{eff}$, the smaller the overall thermal resistance becomes. Figure 2 also shows that the thermal resistance decreases linearly with thermal mass flow rate until it reaches the asymptotic value of $2/hA_{eff.}$

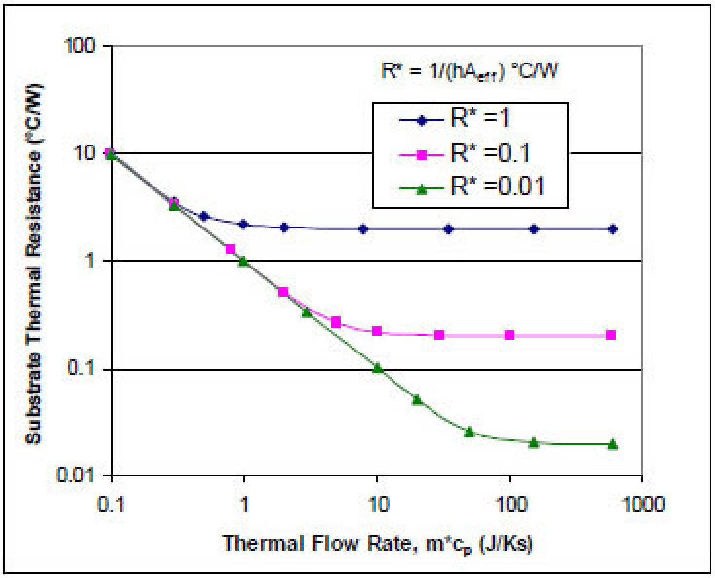

Figure 2. Thermal Resistance as a Function of Thermal Mass Flow Rate [2]

A simple liquid metal cooling loop using an MFD pump was constructed [2].

A substrate was fabricated using polyimide or FR4 laminates. The whole assembly was made from 3 layers of substrates. The middle substrate has channels made for the liquid metal to flow. The two ends of the substrate are bonded to nickel plated copper plates for the hot and cold section of the plates. The overall dimension of the substrate is 7.62 x 25.4 cm. The liquid channels that run through the length of the substrate are 6.35 mm wide and 0.76 mm deep. The magnetic pump has a very simple construction and the whole assembly is shown in Figure 3.

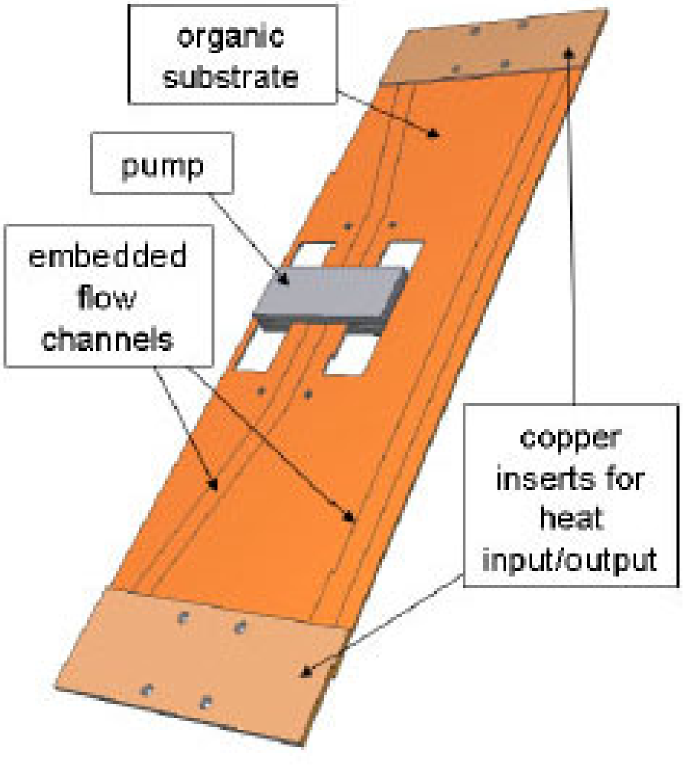

Figure 3. Assembled View of the Substrate [2]

The exploded view of the magnetic pump is shown in figure 4.

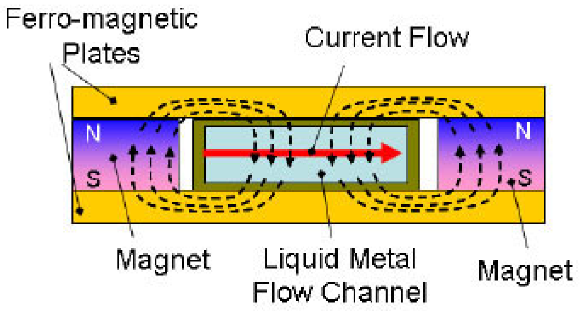

Figure 4. Simple Schematic of the Magnetic Pump [2]

The liquid channels were surrounded by 2 magnets on the sides and covered on top and bottom with ferromagnetic plates. The interaction of the applied current to the fluid and the magnetic forces creates an electromotive force in the direction of the flow.

The entire substrate was tested using simulated heat on the hot side and a TEC on the cold side. An IR image of the temperature distribution is shown in Figure 5.

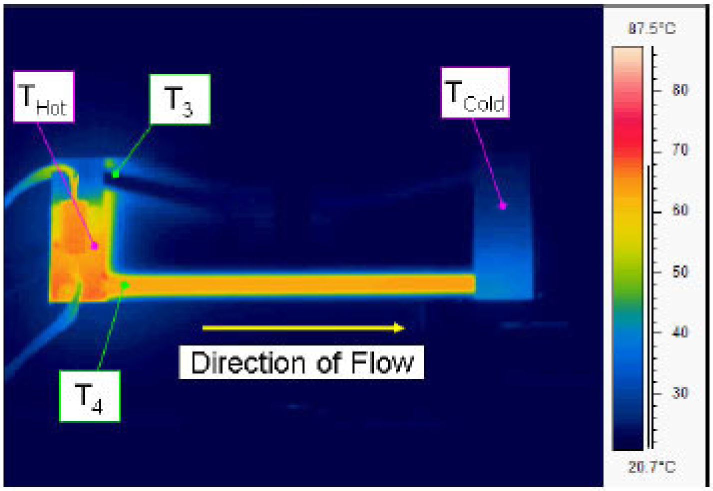

Figure 5. IR Image of the Temperature Distribution in the Substrate [2]

The image clearly shows that, in addition to the hot section, there are temperature gradients in the flow passageway that have to be accounted for. The thermal resistance of the entire assembly is calculated as:

$$R = \frac{T_{hot} - T_{cold}}{Q}$$

Where:
Q = power dissipation (W)
T_{hot} = hot section temperature (°C)
T_{cold} = cold section temperature (°C)

The plot of thermal resistance as a function of pumping power of the magnetic pump is shown in figure 6. The figure shows that with more current through the pump, the thermal resistance decreases. At about 450 mW, thermal resistance has reached an asymptotic value of 0.5 °C/W.

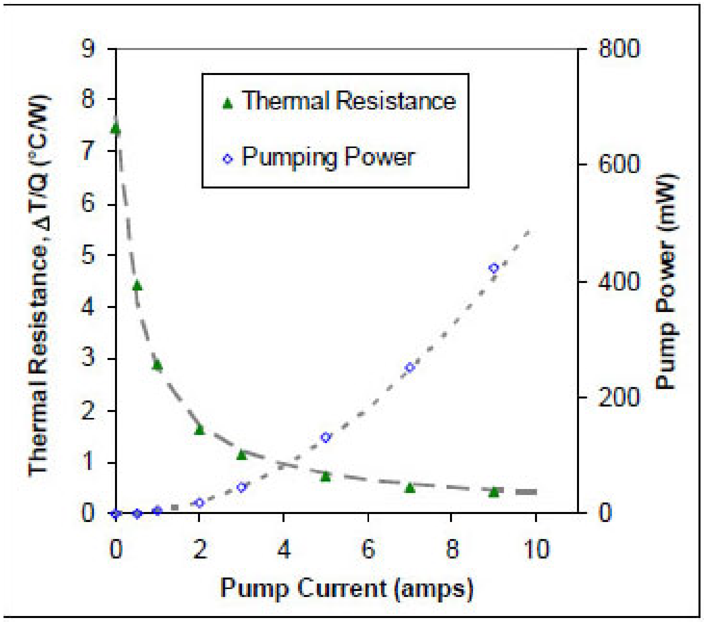

Figure 6. Thermal Resistance and Pumping Power of the Assembly as a Function of Electric Current [2]

Figure 7 shows the pressure drop and mass flow rate of the liquid metal as a function of current. It can be seen that at a high current value of about 10 amps, the flow rate is about 6 gr/s. This corresponds to a Reynolds number of 414. This establishes that the flow is laminar. It is also assumed that the flow is fully developed Based on an aspect ratio of 11 (passage size 11 x 1 mm), the Nusselt number is 6 for uniform heater temperature; so, the heat transfer coefficient can be estimated as:

$$h = \frac{k \times Nu}{D_h} = \frac{16.5 \times 6}{0.00183} = 54{,}000 \text{ W/m}^2\text{K}$$

Where:
k = thermal conductivity of the liquid metal (w/mK)
D_h= hydraulic diameter
Nu = Nusselt number
h = heat transfer coefficient (W/m^2K)

The liquid metal used in this study has the following characteristics:
Density: 6.44 gr/cm^3
Visocisity: 0.0024 NS/m^2
Thermal conductivity = 16.5 W/mK
Specific heat = 0.37 J/gK

The heat transfer areas on the hot and cold side were 7.5 cm^2. This corresponds to:

$$R^* = 1/(hA) = 1/(5400 \times 7.5 \times 10^{-4}) = 0.024\ ^{\circ}C/W$$

Figure 6 shows that the overall thermal resistance at 10 amps (6 gr/s) is about 0.45 °C/W. This calculated result matches with the data in figure 6 at R* = 0.024 °C/W. Figure 6 shows that the thermal resistance approaches asymptotically to 0.45 °C/W as flow rate increases to 6 gr/s at 10 amps.

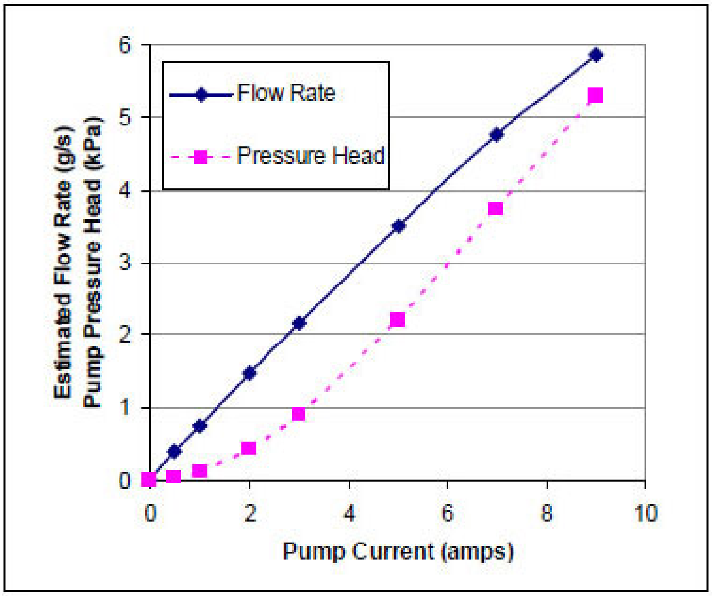

Figure 7. Chip Temperature of the Conventional Heat Sink [3]

It can easily be calculated that the limit of thermal resistance at 10 amps for the liquid loop assuming infinite heat transfer coefficient on the hot and cold surfaces is

$$R = \frac{1}{\dot{m}C_p} = \frac{1}{0.006 \times 370} = 0.45\ ^{\circ}C/W$$

This equation might not be physically correct, because in order to get a very large heat transfer coefficient a very large mass flow is needed, but mathematically it shows that at low flows, the thermal resistance is bound by the mass flow and not the heat transfer coefficient.

As mentioned before, the above the thermal resistance applies only from the hot surface to the cold surface. In a liquid cooling system design, the thermal resistance of the heat sink has to be added to find the overall thermal resistance from junction-to-ambient. In addition to high performance cold plates, the caloric resistance of the circulating fluid has to be considered.

By looking at the equation for thermal resistance, the impact of C_p can be substantial. Ideally, a fluid with best thermal conductivity and heat capacity will perform the best. It has been claimed that liquid gallium is the best liquid metal for cooling applications [4]. Its thermal conductivity is very high at 29.4 W/ (m.°C), compared to water at 0.6 W/ (m.°C), and the liquid metal fluid used in [3], which is 16.5 W/ (m.°C). This can minimize the thermal resistance on the hot and cold plates, since the heat transfer coefficient will be high. But, the specific heat of this liquid metal at 370 J/(kg.K) is much lower than water at 4200 J/(kg.K); but, per volume, is only half the value of water at 2158 kJ/ (m^3.K). The caloric resistance can compete with water flow rate if the product $\dot{m}C_p$ is the same or higher for Gallium. Considering that the density of Gallium is about 6 times of water and its heat capacity is about 11 times lower than water, the volumetric flow rate of Gallium should be at least

1.8 times that of the water to compete with its caloric resistance. The only liquid metal that has a heat capacity comparable to water is Lithium, but this is a very toxic material and its use in thermal management will probably never materialize. The only drawback of water is that the magnetic pump will not work with water.

Ma and Liu [5] also introduced nano particles into liquid metals to enhance the thermal conductivity in addition to liquid metals. More work is needed to see the potential of this new liquid.

Using liquid metal in electronics cooling is both challenging and exciting. The idea of not having a mechanical pump is very appealing. However, the high Amperage needed for the MFD pump is still a challenge, in addition to leakage and fouling issues. Certainly, this is one more innovative way in electronics cooling that requires more research.

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