The Thermal Resistance of Microchannel Cold Plates

The trend towards ever higher power dissipation rates has pushed liquid-cooled cold plate designers to look for more effective methods and structures to transfer heat from device to liquid. The heat dissipation level of a liquid-cooled cold plate is determined by the heat conduction in solids and the heat convection in fluids. Normally convection is the dominant factor for reducing the thermal resistance when highly conductive material is used to fabricate the heat sinks. In most cases, the single-phase flow inside microchannels is a laminar flow. For a fully developed laminar flow in a square channel, with constant wall temperature or constant wall heat flux, the Nusselt number is a constant. The heat transfer coefficient can be calculated by the following equation,

$$h = \frac{Nuk}{D_h} \Rightarrow h \frac{1}{D_h}$$

The heat transfer coefficient is inversely proportional to the channel hydraulic diameter. Microchannels can be directly etched on silicon or ceramics or they can be machined on metal. Different materials have different properties. For example, the copper cold plates are widely used in personal computers to cool the CPUs. Silicon/ceramic microchannels have potential applications in integrating on-chip cooling.

This paper studies how the channel size and material affects the overall thermal resistance of cold plate. The cold plate studied is illustrated in Figure 1. The cold plate has base size of 40 X 40 mm. The channel width is a and channel height is b. The cold base thickness is t. The water is chosen as the working fluid.

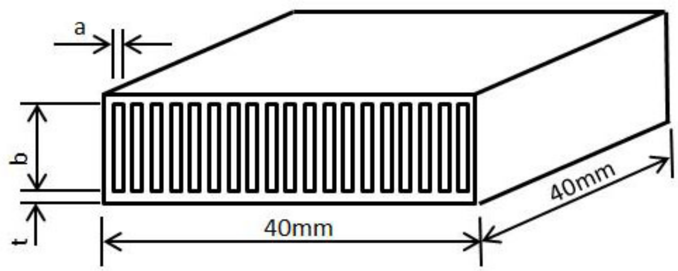

Figure 1. Cold Plate Configuration

Four typical materials are used to study the effect of thermal conductivity on cold plate performance. The properties of these four materials are listed in Table 1.

Material	Density (kg/m³)	Thermal Conductivity (W/°C.m)	Specific Heat (kJ/kg°C)
Silicon	2330	148	0.71
Aluminum Nitride	3200	270	0.76
Copper	8933	398	0.39
Diamond	3500	2000	0.55

Table 1. Typical Cold Plate Material Properties

The overall thermal resistance of a microchannel cold plate is defined as

$$R = \frac{T_{cp} - T_{w\_inlet}}{q}$$

Where T_{cp} is the cold plate base temperature, T_{w_inlet} is the water temperature at the cold plate inlet, and q is the heat flux dissipated by the cold plate. The overall thermal resistance of a microchannel cold plate can be calculated by the following equation,

$$R = R_{spreading} + R_{conduction} + R_{convection} + R_{caloric}$$

Where,

$R_{spreading}$ is the heat spreading resistance between heat source and cold plate

$R_{conduction}$ is the conduction resistance of cold plate base

$R_{convection}$ is the convection resistance between microchannel fins and water

$R_{caloric}$ is the liquid caloric thermal resistance due to temperature rise of water

To simplify the analysis, the heat source base is assumed to be the same size as the cold plate. So, the heat spreading resistance between the heat source and the cold plate is zero. For calculating the heat spreading resistance due to the size difference between the heat source and cold plate base, please refer to a previous Qpedia paper entitled "Spreading Resistance of Single and Multiple Heat Sources" in the September, 2010 issue [1].

The base conduction resistance is affect by material, base size and base thickness,

$$R_{conduction} = \frac{t}{kA}$$

Where k is solid thermal conductivity, t is cold plate base thickness, and A is cold plate base area.

For the studied cold plate, the base size is 40 X 40 mm, the conduction thermal resistance for different material and base thickness is shown in Table 2. The conduction thermal resistance is very small and is only a small portion of overall cold plate thermal resistance, even for a silicon-made cold plate.

	$R_{conduction}$(°C/W)			
Base Thickness (mm) / Material	0.25	0.5	0.75	1
Silicon	0.00106	0.00211	0.00317	0.00422
Aluminum Nitride	0.00058	0.00116	0.00174	0.00231
Copper	0.00039	0.00079	0.00118	0.00157
Diamond	0.00008	0.00016	0.00023	0.00031

Table 2. Cold Plate Conduction Thermal Resistance

The liquid caloric thermal resistance is inversely proportional to the fluid volumetric flow rate,

$$R_{calotic} = \frac{1}{2\dot{m}C_p}$$

Where $\dot{m}$ is the water mass flow rate, and C_p is the water specific heat. Table 3 shows the calculated liquid caloric thermal resistance at different flow rates. At an operating condition of 2 LPM (liter per minute), the resistance is around 0.0036 ºC/W.

Water Flow Rate (LFM)	0.5	1	2	4
$R_{calotic}$ °C/W	0.0143	0.0071	0.0036	0.0018

Table 3. Liquid Caloric Thermal Resistance

The convection thermal resistance is dictated by the following equation,

$$R_{convection} = \frac{1}{\eta hA}$$

Where η is the fin efficiency, h is the heat transfer coefficient of the fin, and A is the total fin surface area. Three different fin configurations (CP1, CP2, and CP3) are studied. The channel aspect ratio is kept at a constant of 15. All three fin configurations have similar fin surface areas, but their hydraulic diameter D_h is different, which leads to a different fin heat transfer coefficient. The smaller the hydraulic diameter, the larger the heat transfer coefficient. The detailed information for the three different configurations is listed in Table 4.

	Fin Thickness (mm)	Fin Height (mm)	Channel Width (mm)	Base Thickness (mm)	# of Fins	A (mm^2)	D_h (mm)	h ($W/m^2 \cdot °C$)
CP1	0.75	11.25	0.75	1	26	23400	1.406	2987
CP2	0.5	7.5	0.5	1	40	24000	0.938	4480
CP3	0.25	3.75	0.25	1	80	24000	0.469	8960

Table 4. Three Fin Configurations

For cold plates made of silicon, the calculated thermal resistance is shown in Table 5; all results are for 2 LPM flow and 0.5 mm base thickness. The fin efficiency of the silicon cold plate is relatively low (<40%) due to the low conductivity of silicon. In the case of the 0.5 mm channel (CP2), the convection thermal resistance is 81% of the overall thermal resistance.

	η	$R_{spreading}$ (°C/W)	$R_{conduction}$ (°C/W)	$R_{convection}$ (°C/W)	$R_{caloric}$ (°C/W)	R (°C/W)
CP1	0.376	0	0.0021	0.0381	0.0036	0.0438
CP2	0.377	0	0.0021	0.0247	0.0036	0.0304
CP3	0.378	0	0.0021	0.0123	0.0036	0.0180

Table 5. Thermal Resistance of Silicon Cold Plate

The calculated thermal resistance for the aluminum nitride cold plate is shown in Table 6. Compared to silicon cold plate, its fin efficiency is higher (~49%) and the overall thermal resistance is low. In the case of the 0.5 mm channel (CP2), the convection thermal resistance is still round 79% of the overall thermal resistance.

	η	$R_{spreading}$ (°C/W)	$R_{conduction}$ (°C/W)	$R_{convection}$ (°C/W)	$R_{caloric}$ (°C/W)	R (°C/W)
CP1	0.492	0	0.0012	0.0291	0.0036	0.0338
CP2	0.494	0	0.0012	0.0188	0.0036	0.0236
CP3	0.495	0	0.0012	0.0094	0.0036	0.0141

Table 6. Thermal Resistance of Aluminum Nitride Plate

The calculated thermal resistance for the copper plate is shown in Table 7. Its fin efficiency increases to around 57% and the overall thermal resistance is 13% lower than that of the aluminum nitride cold plate. In the case of the 0.5 mm channel (CP2), the convection thermal resistance is around 79% of the overall thermal resistance.

	η	$R_{spreading}$ (°C/W)	$R_{conduction}$ (°C/W)	$R_{convection}$ (°C/W)	$R_{caloric}$ (°C/W)	R (°C/W)
CP1	0.574	0	0.0008	0.0249	0.0036	0.0293
CP2	0.576	0	0.0008	0.0162	0.0036	0.0205
CP3	0.577	0	0.0008	0.0081	0.0036	0.0124

Table 7. Thermal Resistance of Copper Plate

The calculated thermal resistance for the diamond plate is shown in Table 8. Its fin efficiency jumps to 86% and the overall thermal resistance is 29% lower than that of the copper cold plate. As for the 0.5 mm channel (CP2), the convection thermal resistance is around 74% of the overall thermal resistance. In the case of the 0.25 mm channel (CP3), the convection thermal resistance drops to 59% of the overall thermal resistance. Here, the $R_{caloric}$ starts to have a larger impact on the overall thermal resistance.

	η	$R_{spreading}$ (°C/W)	$R_{conduction}$ (°C/W)	$R_{convection}$ (°C/W)	$R_{caloric}$ (°C/W)	R (°C/W)
CP1	0.858	0	0.0002	0.0167	0.0036	0.0204
CP2	0.859	0	0.0002	0.0108	0.0036	0.0146
CP3	0.859	0	0.0002	0.0054	0.0036	0.0091

Table 8. Thermal Resistance of Diamond Cold Plate

From the above data, it is obvious that by using good material and a microchannel structure, cold plates can achieve amazingly low thermal resistance rates. For example, the copper cold plate with 0.5 mm wide channels can display a thermal resistance of 0.0205 ºC/W for a 40 X 40 mm size, which translates to a unit thermal resistance of 0.33 $ºC/W/cm^2$. If the heat source has a heat flux of $100W/cm^2$, the temperature rise caused by the cold plate is only 2.1ºC.

Through the above comparisons, it is clear that materials with higher thermal conductivity will have better thermal performance. Diamond is the best, but there is no feasible way to justify its cost for cooling commercial products. Copper is a very good choice for cold plates used to transfer heat from higher power chips to water.

On the other hand, reducing the hydraulic diameter of the channel will dramatically decrease the convection resistance. However, there are two drawbacks for reducing the hydraulic diameter of the channel. First, it will greatly increase the pressure drop across the channel, which leads to more pumping power required for the pump. Second, the smaller channel size will have more chance of clogging due to particles inside the working fluid, which requires finer filtering system.

For high performance cold plates, the $R_{caloric}$ will be an important factor on overall thermal resistance, besides convection thermal resistance. The only way to reduce it is by increasing the liquid flow rate, which will lead to more pressure drop and this then requires a better pump. When designing a cutting edge cold plate, engineers should pay a lot of attention to pressure drop, pumping power, system complexity and reliability while pursuing high performance.

References:

1. **"Spreading Resistance of Single and Multiple Heat Sources", Qpedia, September, 2010, Advanced Thermal Solutions, Inc.**