Pushing the limits of liquid cooling: Design and analysis of a direct liquid cooling system for power modules

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The Power Point Presentation will be available after the conference.

Abstract

Direct cooling of power modules offers significant advantages over traditional cooling technologies using coldplates. Essentially, direct cooling of power modules eliminates the layer of TIM (Thermal Interface Material) needed between the module and the coldplate yielding to a much lower thermal resistance. As a consequence of such improvement lower operating temperatures or, conversely, high power densities can be achieved. Additionally, direct cooling of power modules offers a more compact, reliable, and cost effective cooling technology than traditional coldplates.
Design and analysis of a new direct cooling integrated system for power modules will be presented in this work. It is concluded that the new proposed integrated cooling concept could improve by up to 70% the thermal performance of the system compared to a traditional coldplate design. Suppression of the TIM layer allows to take advantage of the promising micro deformation technology (MDT) to create optimal fin and pin geometries 'pushing the limits' of liquid cooling restricted, usually, by the low thermal performances of the traditional coldplate designs.

1. Introduction

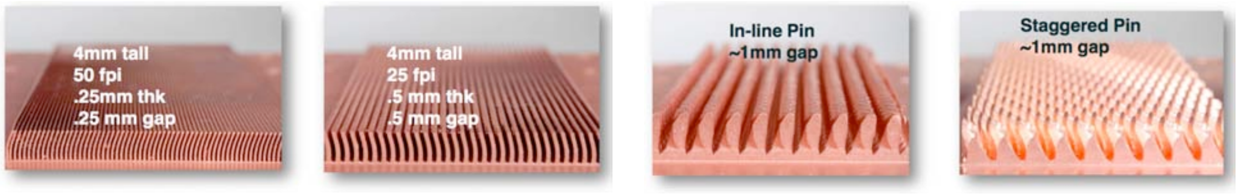
Power electronics are used in many different applications from inverters in hybrid and electric vehicles, power conversion for wind and solar, traction drives for trains, to MRI amplifiers. Generally the higher power applications require liquid cooling of the power electronics. Assembling power modules on liquid-cooled coldplates is a well-known method for increased cooling. Typical coldplates are simple, large channels in aluminium plates, or cooper tubes pressed into aluminium slabs. Recently, straight fin micro-channels and pin fin cold plates geometries are becoming popular because of the high power densities to be dissipated. Nonetheless, tends in power electronics systems have placed increasing demands on the efficiencies of the thermal management systems for the power modules. Increases in switching frequencies and voltages ratings of IGBTs as well as denser packing of the die reflect that the cooling capacity of present modules are approaching current liquid cooling limits. Faced with this challenges and limitations, new module cooling solutions need to be explored.

1.1. Advantages of direct liquid cooling

High-power electronics comprise a number of silicon power dies soldered onto one or more substrates, which are usually direct bounded copper (DBC) metalized ceramics soldered into a base plate. The module is then mounted into a liquid cooled base plate by means of a thermal interface material (TIM). Much of the overall thermal resistance occurs between the module's base and the liquid-cooled cold plate. Direct liquid cooling eliminates the TIM and associated thermal resistance and the liquid directly flows to the backside of module. The DBC substrate is then directly joined to the liquid cooled coldplate eliminating the thermal barrier of the TIM. Moreover, eliminating the TIM material barrier allows to develop high-performance coldplates with high inner heat exchange properties as the improvement in the coldplate is no longer negligible.

1.2. Coldplate geometries and manufacturing methods

Standard manufacturing methods like machining or forging can be used to create the typical straight fin and round staggered pin fin cold plate geometries. Promising Micro Deformation Technology (MDT) is now available to create optimal fin and pin geometries. MDT is able to create custom, high performance mezzo and micro-channels as well as new pin and fin geometries suitable for liquid cooling applications. This patented process employs a fixed tool, which mechanically and plastically deforms the work piece to form finite and repeatable fin and pin patterns. Unlike machining or etching this is not a subtractive process, and no metal is wasted. MDT Technology is highly flexible and can create a wide variety of fin, pin and micro-channels geometries.



(a) Fins (b) Pins

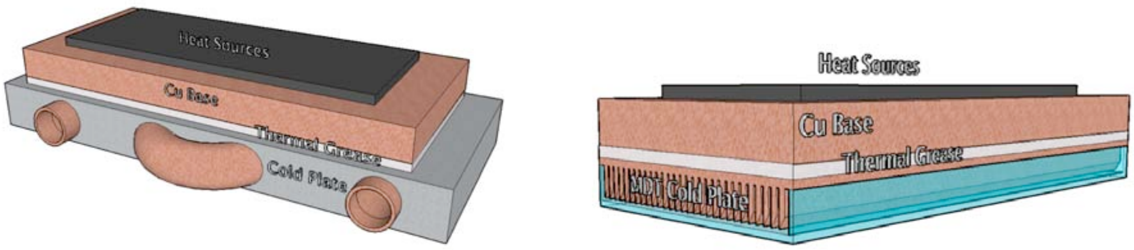
Fig. 1. Samples of MDT geometry options

2. Design of a direct liquid system for power modules

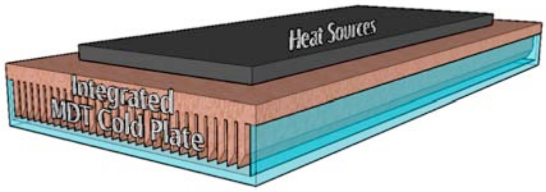
Because of the advantages mentioned above direct liquid cooling appears to be a realistic method to face challenges and limitations of the current liquid cooling module solutions. Additionally direct liquid cooling will provide room for improvement and it will also allow to anticipate future thermal management needs.

Design methodology combines two complementary means of improving the effectiveness of the power module:

1. Reducing the thermal resistance by eliminating layers between the die and the cooling media
2. Increasing efficiency of the coldplate by improving heat transfer rate from the colplate to the coolant



(a) Copper tubes into aluminum slab (b) MDT micro-channels coldplate



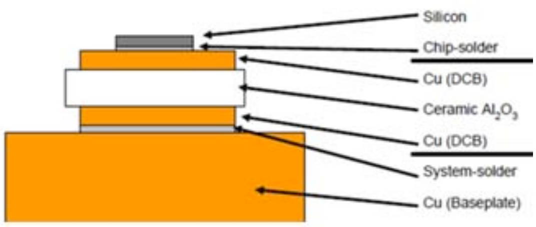
(c) MDT Integrated cold plate

Fig. 2. Conventional and proposed coldplate designs for comparison

In order to explore means of improving effectiveness of the power module, coldplates designs in Fig. 2 are considered. While comparison between (a) and (b) captures improvement of the heat transfer rate of the cold plate to the coolant, comparison between (a) and (c) captures improvement due to the suppression of the TIM material.

3. Analysis of a direct liquid system for power modules

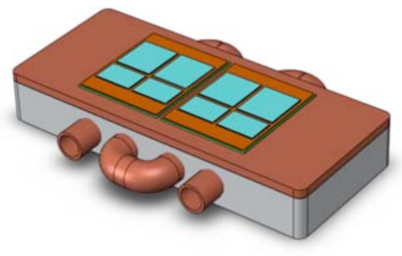
Computational Fluid Dynamics (CFD) was used to characterize the coldplates. Generated CFD models for the simulations included DBC layer decomposition. Fig. 3 shows layer decomposition and corresponding physical properties. The aim of this added complexity is to include the package heat spreading effect in the numerical model in order to provide more realistic results. Most of the results reported in the literature included only the cold plate, the calculated thermal resistivity of the die, DBC AIN and appropriate solder layers need to added to determine the overall thermal resistivity from the junction to the inlet water.



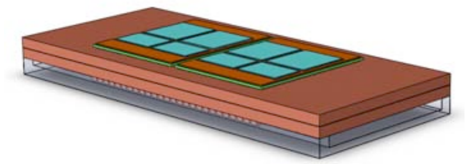
material	length	width	thickness	Voids	Conductivity	Density
	mm	mm	mm	%	W/mC	g/cm^3
Silicon Carbide	13.50	24.70	0.250	0%	380.0	3.10
Solder CHIP	13.50	24.70	0.100	10%	35.8	8.52
Copper	33.20	31.00	0.305	0%	385.0	8.96
AN 180, 99%	38.70	32.00	0.635	0%	170.0	3.26
Copper	37.70	31.00	0.305	0%	385.0	8.96
Solder Low	37.70	31.00	0.100	10%	35.8	8.52

Fig. 3. DBC Layer decomposition and properties used to calculate total DBC thermal resistivity

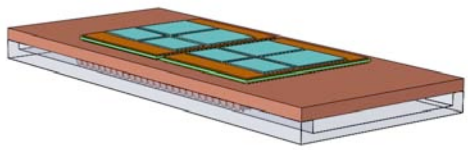
According to the design guidelines established previously, three 3D-models of power modules were generated for the CFD simulations.



(a) Basic coldplate with TIM



(b) MDT coldplate with TIM



(c) Integrated MDT coldplate (direct cooling)

Fig. 4. 3D numerical models

MDT in-line pin fin structure was selected for the MDT coldplates. Based on a previous numerical and experimental study [2] as it provides the best thermal performance per pressure drop. The twisted pin shape adds turbulence and breaks up of boundary layer increasing the heat transfer coefficient with only a minimal impact on the pressure drop when compared to a straight fin or round pin fin.

The cooling fluid is water and the inlet temperature was set to 65ºC. The flow rate range was varied between 2 l/min and 6 l/min. They were 8 dies per module and the total power to be dissipated was set 350 W.

4. Results

Fig. 5 shows velocity streamlines and velocity contour plots for the MDT coldplate. It is important to point out how MDT in-line pin fin geometry insures a uniform flow distribution avoiding dead zones, which could lead to non-desirable high temperature gradients and potential hot-spots.

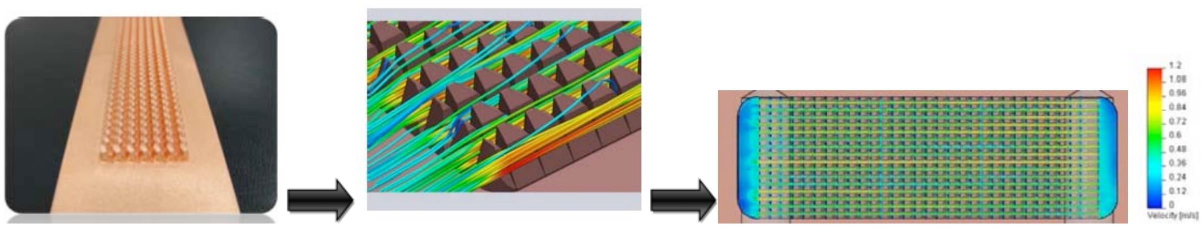


Fig. 5. MDT in-line pin fin coldplate: Velocity plots

Fig. 6 shows variation of the thermal resistance versus flow rate. As expected Integrated MDT coldplate induces a significance reduction in the thermal resitance.

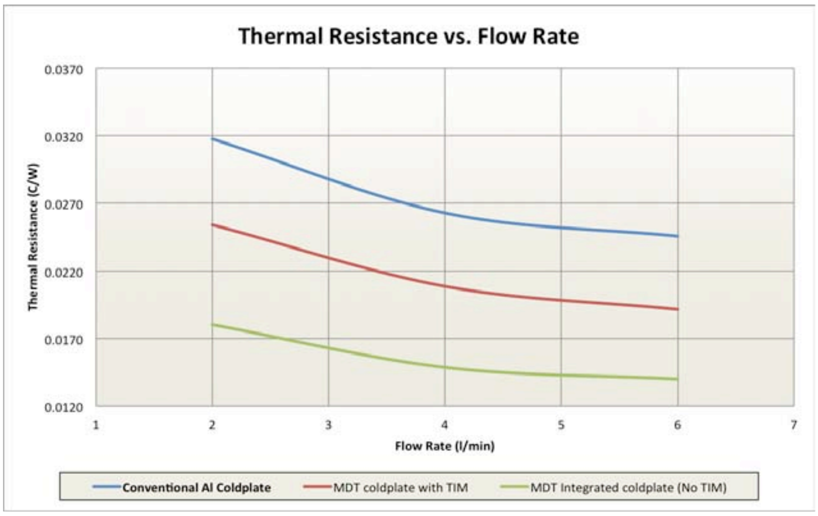


Fig. 6. Thermal resistance vs flow rate

Fig. 7 shows variation of the max surface temperature versus flow rate. Integrated MDT coldplate induces the lowest coldplate surface temperature.

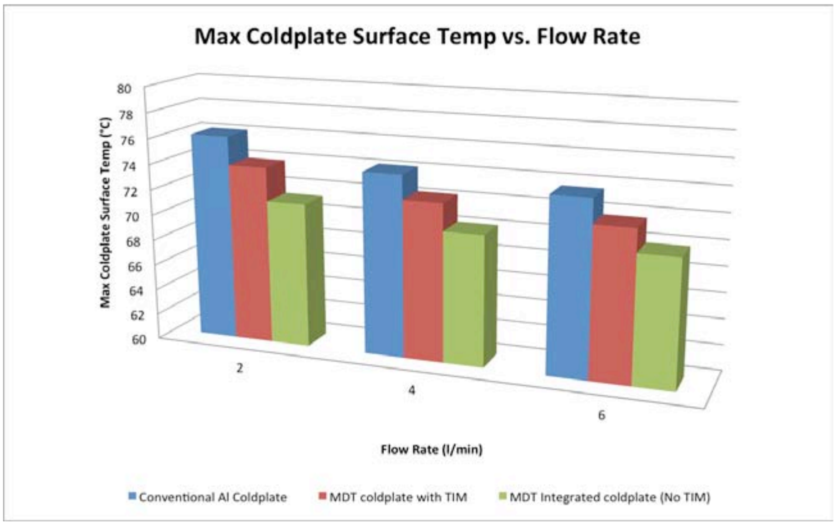


Fig. 7. Max. coldplate surface temperature vs flow rate

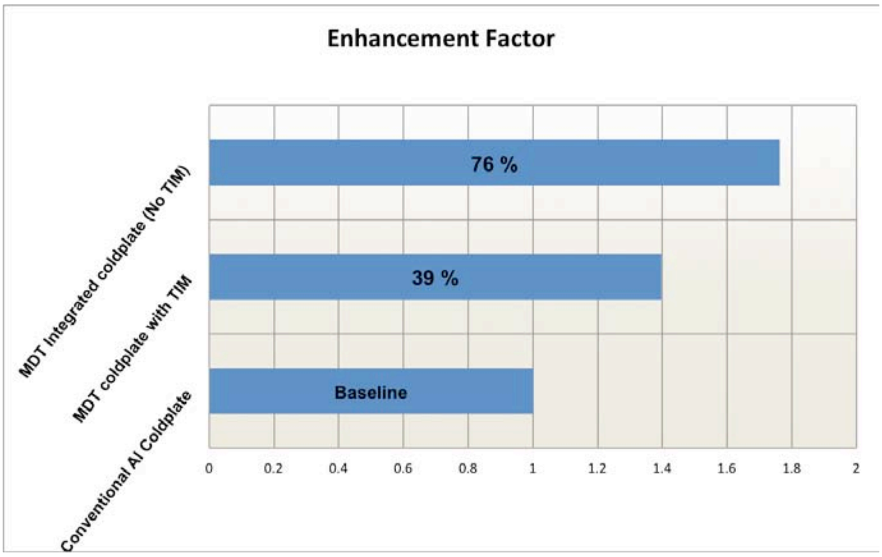


Fig. 8. Thermal resistance enhancement factor

5. Conclusion

Results show that eliminating the thermal interface material (TIM) layer lead to a significant enhancement of the thermal performances in power electronics modules. Moreover, suppression of the TIM layer allows to take advantage of new technologies and manufacturing methods to improve heat transfer rate from the coldplate to the coolant. Direct liquid cooling of power modules, combined with new technologies and coldplate manufacturing methods appears to be a realistic approach to anticipate future thermal management needs of the power electronics systems.

6. Literature

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