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Published in:
Proceedings of the 18th European Conference on Power Electronics and Applications (EPE'16 ECCE-Europe), 2016

DOI (link to publication from Publisher):
10.1109/EPE.2016.7695575

Publication date:
2016

Document Version
Accepted author manuscript, peer reviewed version

Optimization Tool for Direct Water Cooling System of High Power IGBT Modules

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Acknowledgements

The authors would like to thank Danfoss Silicon Power GmbH for their support and providing device and cooling system information.

Keywords

«Cooling», «IGBT», «Modelling», «Thermal design», «Reliability»

Abstract

Thermal management of power electronic devices is essential for reliable system performance especially at high power levels. Since even the most efficient electronic circuit becomes hot because of ohmic losses, it is clear that cooling is needed in electronics and even more as the power increases. One of the most important activities in the thermal management and reliability improvement is the cooling system design. As industries are developing smaller power devices with higher power densities, optimized design of cooling systems with minimum thermal resistance and pressure drop become important issue for thermal design engineers. This paper aims to present a user friendly optimization tool for direct water cooling system of a high power module which enables the cooling system designer to identify the optimized solution depending on customer load profiles and available pump power. CFD simulations are implemented to find best solution for each scenario.

Introduction

Power electronic devices like Insulated Gate Bipolar Transistors (IGBTs) generate heat losses up to several hundred watts during normal operation. The heat is generated in semiconductor chips due to conduction and switching losses. Although the generated losses are small portion of the total power converted, but it can result in large heat loads. Moreover, as the devices and packages become smaller, the generated losses lead to extremely large heat fluxes at chips – typically 300 W/cm^2 and more [1]. Therefore, thermal management of power devices – e.g. cooling system design – becomes crucial for a reliable performance. This is more critical when designing a multi-chip power module for packaging of the power devices, because the thermal coupling effects of chips intensify the heat loads on the chips. The dominant failure mechanisms in the power devices do not only occur because of high absolute temperatures. The amplitude of temperature swings due to power cycling in normal operation may also lead to failures in a power device [2]-[4].

Cooling the high power modules with heat dissipations higher than 300 W/cm^2 is beyond the capabilities of conventional air cooling systems [1]. On the other hand, liquid cooling systems surpass the air cooling systems by supplying heat transfer coefficient several orders of magnitudes higher. So, using liquid cooling system enables much higher power densities of power modules and more compact converter solutions. Today, various water cooling solutions have been introduced which generally are classified in two groups of indirect and direct liquid cooling [5]-[12]. In indirect cooling, the power module is mounted on a closed cooler, e.g. a cold plate, which is fabricated by pressed-in copper tubes in aluminum extrusions or gun drilling holes in aluminum plates. An example of which, is shown in Fig. 1 [13]. A Thermal Interface Material (TIM) is used between the power module and cold plate for higher heat spreading over the cold plate.

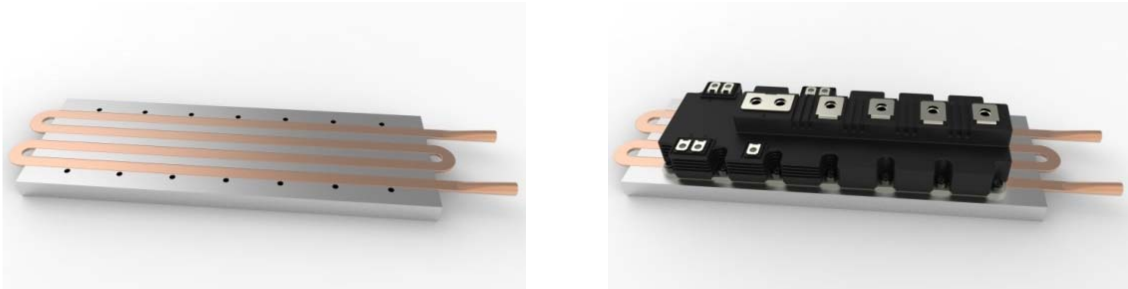


Fig. 1: Cold plate for an IGBT module [13].

On the other hand, in direct liquid cooling systems, the coolant directly contacts the power module without any disturbing layer. A direct liquid cooling system is commonly done by various pin fin designs such as the one, which is shown in Fig. 2 that a high power IGBT module is equipped with a baseplate with pin fins [13]. In direct liquid cooling systems, the efficiency of cooling system increases by increasing the cooling contact surface and eliminating the TIM layer, thus reducing the junction-to-ambient thermal resistance [12]. Direct liquid cooling systems eliminates TIM that is traditionally needed between the power module and the cold plate. Because, the TIM layer accounts for 30%-50% of the junction to coolant thermal resistance, elimination of TIM results in an improved thermal management for the power module. Since the dominant failure mechanisms are due to thermal stresses, this will lead to a higher reliability. However, the design of power module and cooling system parameters should be calculated considering the load cycles and converter topologies.

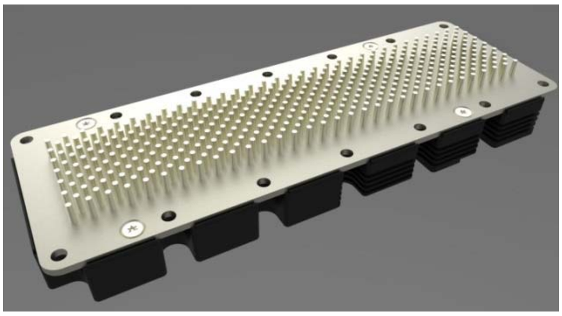


Fig. 2: A baseplate with pin fins for an IGBT module [13].

Today, commercial Computational Fluid Dynamic (CFD) simulators have facilitated the calculations for cooling system design, thus reduced the time-consuming and costly experimental tests. CFD can predict the water flow in fluid channels of cooling system in order to identify correct heat transfers and pressure drop conditions. Heat transfer rates, in turn, can be used for junction temperature calculations in dynamic operation of the power module. In this paper, a design tool for optimization of direct water cooling system is developed using Computer Aided Design (CAD) software. Various physical parameters which influence the performance of cooling system in different applications are studied and applied in the design tool. The design tool is tested by CFD for given operating conditions and performance indexes.

Direct Liquid Cooling System Concept

In the direct liquid system under study, which is named ShowerPower® [13], a plastic turbulator is placed in the layer between the main cooling bath tub and baseplate of the power module, as shown in

Fig 3. The turbulator forces the coolant to flow along the power module baseplate in several isolated cells, and thereby supplying a homogenous cooling of a large baseplate of high power module. Actually the turbulator does not mean a turbulent liquid flow, but a laminar flow under normal flow rates of the coolant. The plastic turbulator consists of several cooling cells in the X and Y directions, which is supplied by a manifold structure on the backside for a uniform water temperature in all channels. Fig. 4 shows the plastic turbulator flow regime. The cold liquid enters the channels and flows through channel fins where heights are less than side walls. This feature provides the power module a two-step cooling: first the cold water enters the channel through the channel inlet and cools down the contact surface of the power module baseplate in the top region of the fins and channels. On the other hand, a portion of cold water flows through the lower region of the channel. The second cooling step of water occurs when the hot and cold water meet in the backside of the fins.

Fig. 3: Power module and cooler [13].

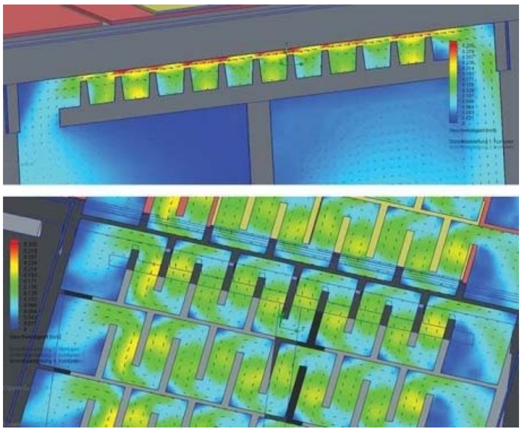


Fig. 4: Plastic turbulator flow vectors and velocity magnitude contours done in CFD simulation.

Considerations in the Design of Cooling System

A cooling system enables more efficient heat transfer from a heat source to the adjacent fluid by using an extended surface area. The performance index that is generally used in the design of cooling systems is thermal resistance. Thermal resistance is a measurement of a temperature difference by which the material resists a heat flow and defines in the conductive heat transfer (Fig 5(a)) as:

$$R_k = \frac{T_1 - T_2}{Q} = \frac{L}{kA} \text{ [K/W]} \tag{1}$$

where R_k is the thermal resistance in the conductive heat transfer, T_1 and T_2 are temperatures in two faces of the material, Q is the heat flux, k is the material thermal conductivity, A is the cross-sectional area, and L is the material's thickness.

The thermal resistance in the convective heat transfer (Fig. 5(b)) is defined as:

$$R_k = \frac{T_S - T_\infty}{Q_h} = \frac{1}{hA} \text{ [K/W]} \tag{2}$$

where R_h is the thermal resistance in the convective heat transfer, T_S is the material's surface temperature, T_∞ is the fluid temperature, Q_h is the heat flux transferred by convection, h is the heat transfer coefficient and A is the surface area.

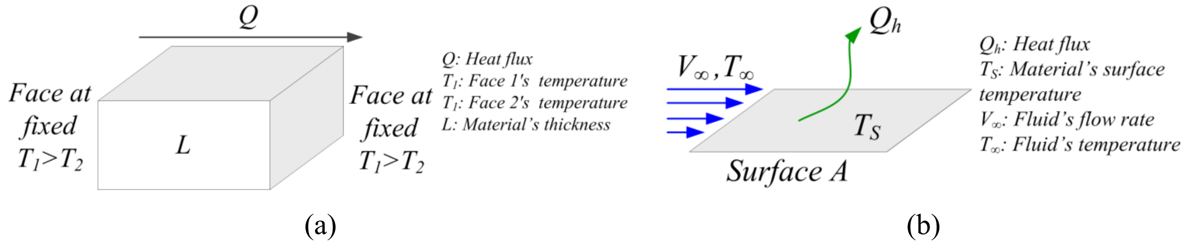


Fig. 5: Heat transfer definition; (a): Conductive heat transfer, (b): Convective heat transfer.

When designing a cooling system, several factors should be considered in order to ensure an optimized layout which delivers the performance needed over the required lifetime of the system. The main factors which influence the thermal resistance of the liquid cooling system are: the contact surface of the coolant, the volumetric flow rate and pressure drop of the coolant, the heat capacitance of the coolant, heat conduction and heat spreading in the heatsink and the coolant temperature [14]. By increasing the contact area of the coolant with the power module, the heat transfer will be improved. In other words, the complex shape of the water cooling system and high flow velocity leads to a turbulent flow which considerably reduces the thermal resistance between the coolant and baseplate of the power module. Knowing the operating points, the thermal resistance can be defined as a function of the volumetric flow rate:

$$R_{th(s-a)_2} = R_{th(s-a)_1} .(\frac{\dot{V}_1}{\dot{V}_2})^K \tag{3}$$

Where $R_{th(s-a)_1}$ and $R_{th(s-a)_2}$ are the thermal resistance between the baseplate and coolant in two operating points, $\dot{V}_1$ and $\dot{V}_2$ are the volumetric flow rate in two operating points, and K is a constant value between 0.3 and 0.5 [14]. In most applications, a pump is utilized to circulate the coolant. The exiting pumping power can be used to provide the required coolant volumetric flow. Pressure drop across the cooling system is a function of squared volumetric flow rate:

$$\Delta P[mbar] = M \times \dot{V}^2 \tag{4}$$

where ΔP is the pressure drop across the cooling system, $\dot{V}$ is the volumetric flow rate and M is a constant value defined by the geometry of cooling system. Increasing the coolant flow rate decreases the thermal resistance, but the pressure drop across the cooling system increases. Therefore, it is tried to keep both parameters at a minimum level as higher the thermal resistance increases the junction temperature and higher pressure drop demands for higher power of the pump.

Optimization Design Tool for Direct Liquid Cooling System

In a case of predefined pump power and volumetric flow rate by customer, a trade-off is needed between thermal resistance and pressure drop in the design of cooling system. The turbulator geometric parameters have high influence on the cooling system performance. These geometric parameters include width of channel, depth of channel, height of fins, number of fins, number of channels and channel cross section area to avoid the risk of blockage (see Fig. 6 and Fig. 7). On the other hand, with less order of importance, cooling bathtub geometries also influence the cooling system thermal performance. The effective bathtub geometric parameters are the main inlet/outlet sizes and the main channel widths.

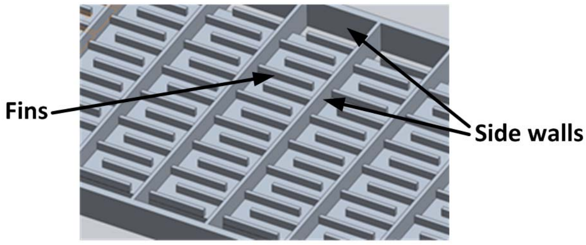


Fig. 6: Fins and side walls in the turbulator of the cooling system.

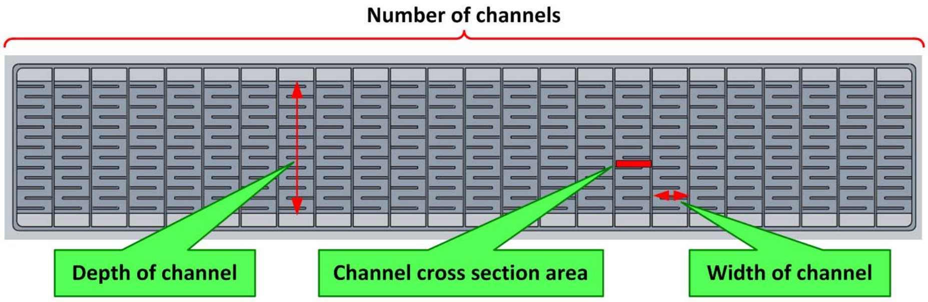


Fig. 7: Geometric parameters in the turbulator of the cooling system.

In order to create different geometries for the cooling system, a design platform is developed in SolidWorks® [15]. For this reason, first the default geometry of the turbulator is modelled. The turbulator of the cooling system under study is designed to cool down the baseplate of a high power IGBT module – PrimePACK 3 IGBT module [16]. Therefore, the size of the turbulator is the same as the effective heat dissipation area (substrate area) and it will not be changed during the parameterization. The minimum thickness of the side walls and fins are also fixed values, which can be fabricated by a CNC milling machine. Since changing in one geometric parameter may affect other parameters, parametrization of geometries starts from inner ones, i.e. the parameters inside one channel. In the next stage, the number of channels is parametrized with dependent variables to the inner geometries.

Besides, the geometric parameters are defined for the cooling bathtub. Fig. 8 shows a cooling bathtub including the gasket space. To improve the efficiency of the cooling system, the efficient cooling area in the contact surface to the baseplate should be increased. For this reason, some solutions are suggested. It has been observed that the gasket thickness is a parameter, which reduces the efficient contact surface of the cooling system. In addition, there has been a useless distance between the turbulator and the screws, so the effective contact surface has been increased by increasing the size of turbulator and use more efficient contact surface. Finally, the inlet diameter of the cooling bath tub has been made variable since the inlet size is effective in pressure drop rate of the fluid in the cooling system.

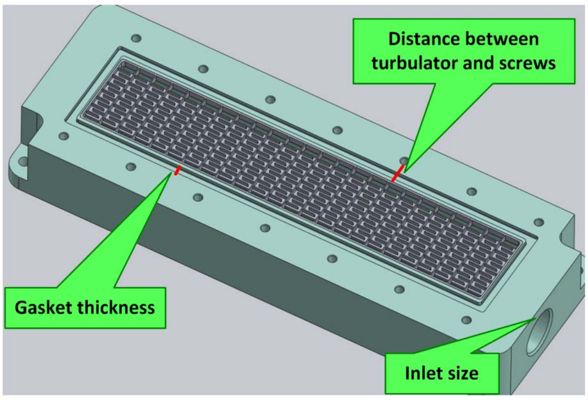
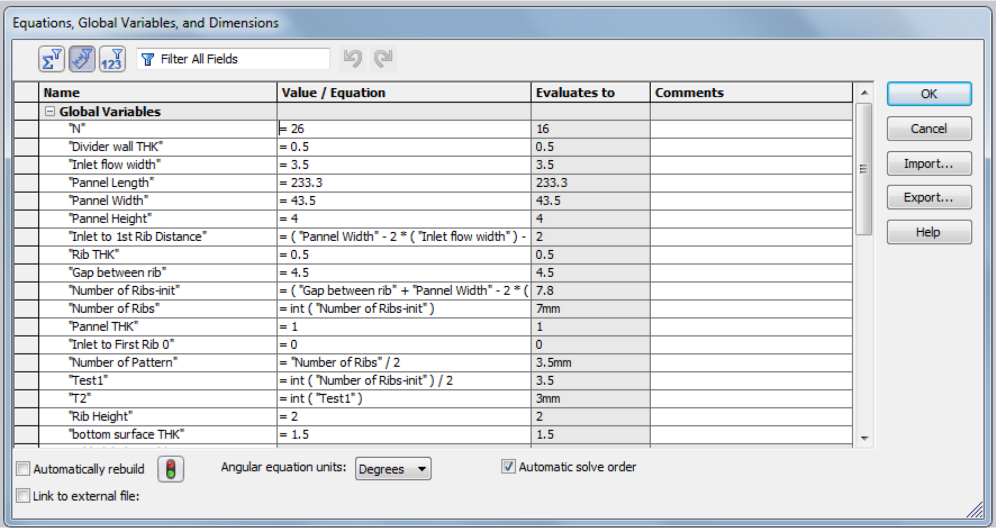


Fig. 8: Geometric parameters in the cooling bathtub of the cooling system.

By using this design platform, the manufacturer changes any effective geometric parameters in both cooling bathtub and plastic turbulator to achieve optimized design according to customer requirements. A view of the developed toolbox in SolidWorks is shown in Fig. 9. The “Global Variables” column includes the geometric parameters, “Value/Equation” column include the geometric relative equations and “Evaluates to” column include the calculated values for each parameter. The default turbulator channels are designed in such a way to have at least one turbulator channel for each IGBT/diode pair as shown in Fig. 10.


Equations, Global Variables, and Dimensions

Filter All Fields

Name	Value / Equation	Evaluates to	Comments
Global Variables			
"N"	= 26	16	
"Divider wall THK"	= 0.5	0.5	
"Inlet flow width"	= 3.5	3.5	
"Pannel Length"	= 233.3	233.3	
"Pannel Width"	= 43.5	43.5	
"Pannel Height"	= 4	4	
"Inlet to 1st Rib Distance"	= ("Pannel Width" - 2 * ("Inlet flow width") -	2	
"Rib THK"	= 0.5	0.5	
"Gap between rib"	= 4.5	4.5	
"Number of Ribs-init"	= ("Gap between rib" + "Pannel Width" - 2 * (	7.8	
"Number of Ribs"	= int ("Number of Ribs-init")	7mm	
"Pannel THK"	= 1	1	
"Inlet to First Rib 0"	= 0	0	
"Number of Pattern"	= "Number of Ribs" / 2	3.5mm	
"Test1"	= int ("Number of Ribs-init") / 2	3.5	
"T2"	= int ("Test1")	3mm	
"Rib Height"	= 2	2	
"bottom surface THK"	= 1.5	1.5	

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Fig. 9: Direct liquid cooling system design platform developed in SolidWorks.

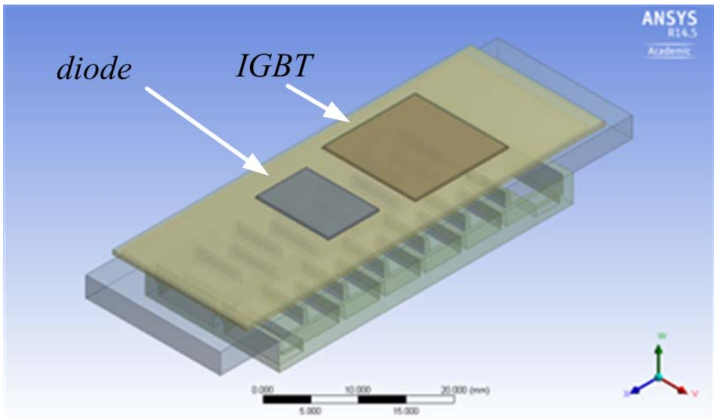

Fig. 10: One section of IGBT/diode pair mounted on a cooling channel of ShowerPower®.

CFD Simulation Verification

To assure the functionality of the design platform, the default cooling system is simulated in a CFD software (ANSYS Icepak [17]) to dissipate heat from a PrimePACK 3 IGBT module as shown in Fig. 11. The simulation is performed with *50 W* power loss in the IGBT chips and *25 W* power loss in the diode chips. The cooling fluid is selected as glycol 50-water 50, volumetric fluid flow rate is set to *5 l/m*, the inlet fluid temperature is fixed to *20 °C* and the output fluid pressure is set to ambient static pressure. Fig. 12 shows the fluid flow inside the channels that confirms the correct operation of cooling system. The temperature profile on the surface of the IGBT module is shown in Fig. 13. In Fig. 13, the original geometry of the turbulator has been used and the maximum IGBT module temperature is *105 °C*.

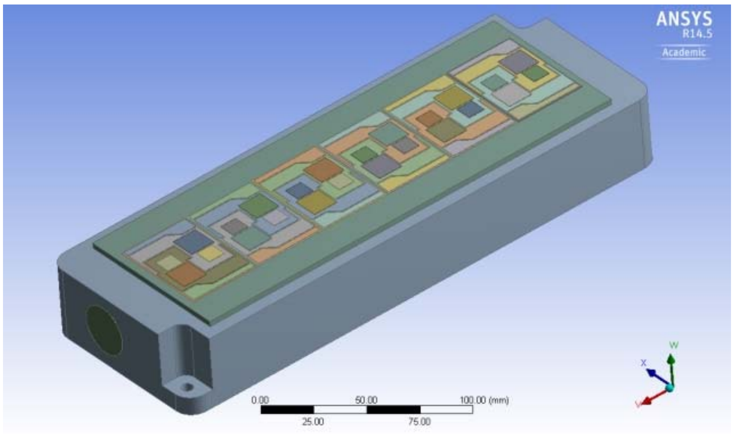

Fig. 11: PrimePACK 3 module mounted on direct liquid cooling system simulated in ANSYS Icepak.

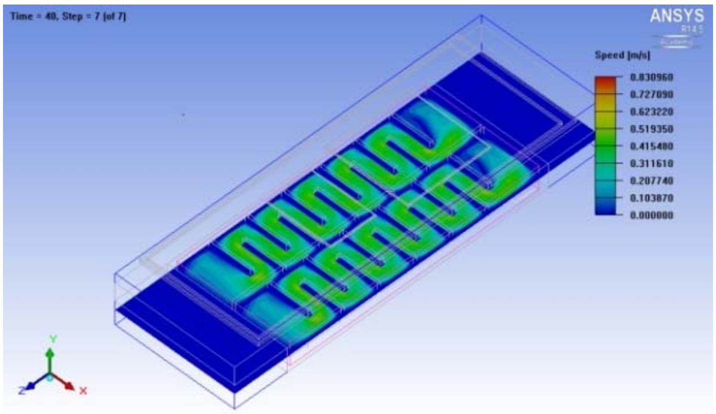

Fig. 12: Fluid flow inside the cooling turbulator of ShowerPower®.

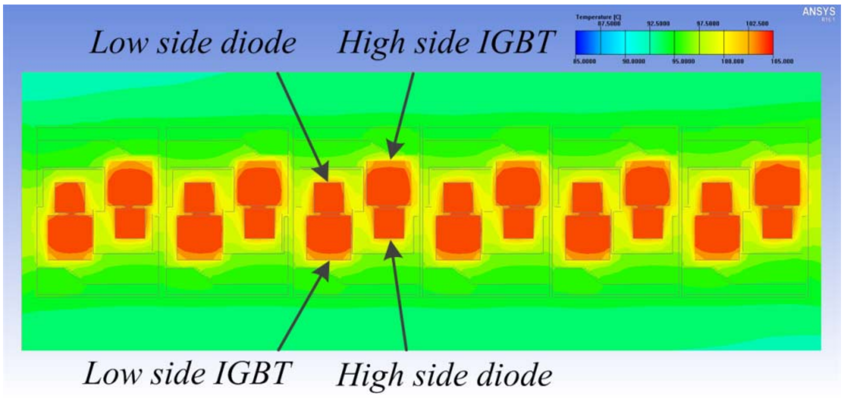

Fig. 13: Temperature profile of the PrimePACK 3 module mounted on direct liquid cooling system.

To verify the optimization tool, as an example, the number of channels in the tabulator is set as a performance index. The CFD simulations are implemented for different numbers of channels from 15 to 40. The number of channels in the original geometry is 24. As it is seen in Fig. 14, depending on the customer's available pump capability, the optimum number of channels for the turbulator can be selected. For example for a pump with pressure drop of 100 mbar, the best solution with a minimum thermal resistance is 26 channels. In Fig. 15, the temperature profile of the IGBT module is shown that a turbulator with 26 channels is used. Comparing to Fig. 13, the performance has been improved by 10% decrease in the chip temperatures.

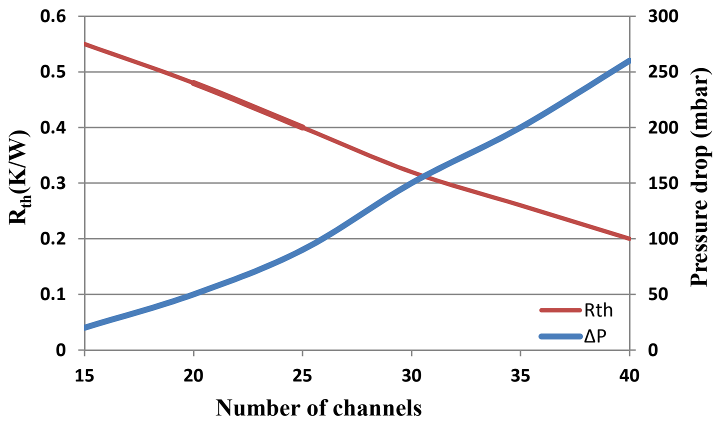

Fig. 14: Thermal resistance, $R_{th(j-a)}$, and pressure drop, ΔP, performance curves vs. number of turbulator channel numbers.

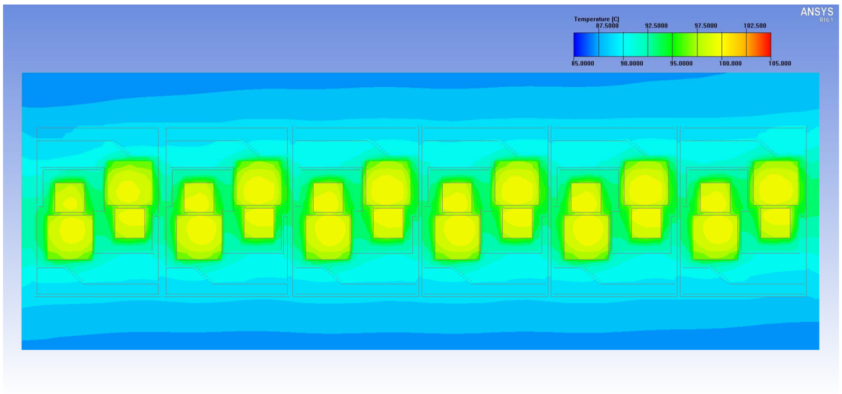

Fig. 15: Temperature profile of the IGBT module mounted on a cooling system with 26 channels.

Another example is shown in Fig. 16 with changing the number of fins in a channel. As it is seen the numbers are changed from 2 to 20. In the original geometry the number of fins in the channels of turbulator is 14. In this example with a predefined pressure drop of 100 mbar, 10 fins give the lowest thermal resistance in the channel. In Fig. 17, the temperature profile of the IGBT module is shown that channels with 10 fins are used. Comparing to the original geometry, the performance has been improved and chip temperatures have been decreased by 6%.

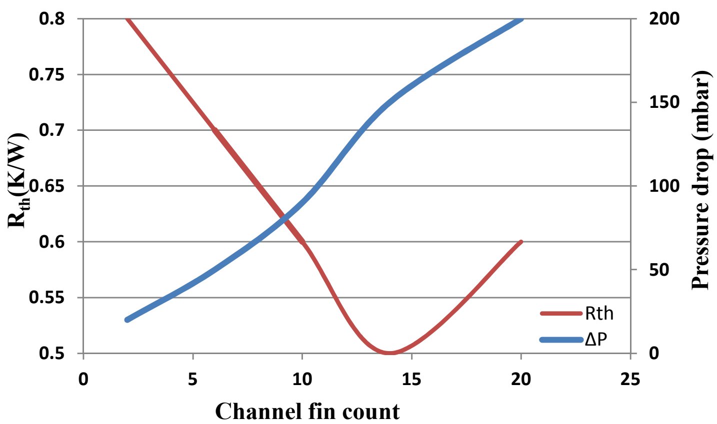

Fig. 16: Thermal resistance, $R_{th(j-a)}$, and pressure drop performance curves vs. fin count in a turbulator channel.

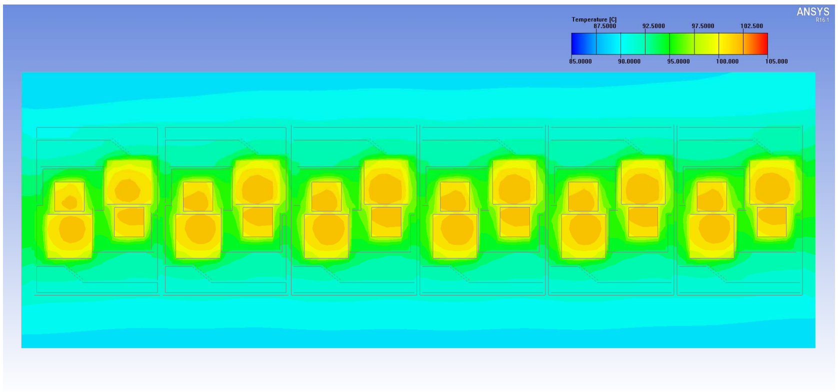

Fig. 17: Temperature profile of the IGBT module mounted on a cooling system with 10 fins per channel.

Conclusion

In this paper, an optimization tool for direct water cooling system of high power IGBT modules has been introduced. The concept of cooling system for high power modules has been explained. Different types of water cooling systems, their pros and cons have been briefly discussed. According to the discussions, the operating principles of ShowerPower® cooling system have been explained, which shows high efficiency in dissipating the heat homogenously. It has also been shown that depending on the cooling system application, minimum thermal resistance and minimum pressure drop are required to keep the chip junction temperature low along with saving power of cooling system pump. Therefore, a design tool has been developed which can be used to optimize the geometries of the cooling system. Finally, CFD simulation results have been presented to validate the operation of design tool in extraction of optimized cooling system. Using this design platform will enable the manufacturer to design an optimized cooling system depending on the heat generated in the IGBT module and the existing pump power. This tool increases the efficiency of cooling system as well as reliability of IGBT module for different mission profiles. The cooling system manufacturer can fabricate the optimized plastic turbulator depending on the application by 3D printing with minimum manufacturing costs.

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