

Thermal-Fluid Dynamic FEM Simulation of Advanced Water Cold Plates for Power Electronics

F. Giuliani, N. Delmonte*, and P. Cova

Dipartimento di Ingegneria dell'Informazione, University of Parma, Parma, Italy

*Corresponding author: Viale G.P. Usberti 181/A, 43124 Parma, Italy, nicola.delmonte@unipr.it

Abstract: The aim of this work is to develop a thermal-fluid dynamic FE model, accurate enough to be used for liquid heatsink design. Power electronic converters such as those for *High Energy Physics Experiments* (HEPEs) or offshore renewable energy systems, must operate in hostile environment with tight thermal constraints. Due to the high power density, the presence of closed environments and the requirement of non-thermal interaction with other subsystems, a liquid cooling system is mandatory. 3D FEM simulation can be used to analyze thermal fluid dynamic behaviour of those systems and can be a useful support for designing heat sinks optimized for specific applications. The paper ends with a comparison between two different water cold plates conceived on purpose for a particular power electronic converter.

Keywords: Water cold plate, Electronics cooling, Thermal-Fluid Dynamic, Conjugate Heat Transfer COMSOL Simulation.

1. Introduction

This paper concerns the design of a specific heat sink for cooling electronics of the power converters that will be used to supply the detection and acquisition systems of ATLAS experiments at CERN, in Geneva [1]. This apparatus is located in an underground tunnel about 100 m depth, then thermal management is critical because of high density integration and for the strict constraint of negligible thermal interaction between the power converter and surrounding electronics, even in case of high dissipated power.

Dealing with these heat rejection problems, liquid cooling system is the most effective way to ensure electrical performances and improve reliability of those systems.

Cold plates are the core parts of these liquid cooling systems, whose efficacy is crucial to the thermal dissipation of the whole system. Important parameters in the design of a water-

cooled cold plate are the followings: thermal performance, water flow rate, pressure drop, mechanical strength, corrosion, cost and so on. Due to the high number of degrees of freedom, the design of cold plate for critical applications is a not obvious task.

The use of numerical simulation and computational techniques to design, evaluate and compare different solutions of custom heat sink allows to save time and expenses associated with analytical design methods and trial-and-error physical prototyping.

Before using this method we assessed the accuracy of the model that we can build with a FE software as COMSOL Multiphysics.

2. Modeling validation

In order to setup the numerical model and verify its accuracy, experiments and simulations of a known cold plate (Figure 1) have been carried out. The thermal performances of this cooling device were characterized at various liquid flow rates and compared with simulation results in the same operative conditions.

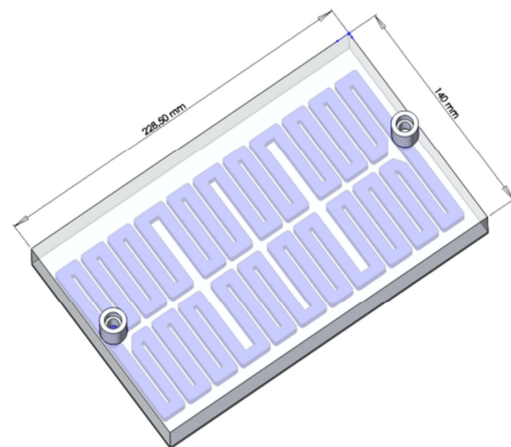


Figure 1. 3D geometry of the test cold plate.

This cold plate has been designed for high power electronics and we choose it as benchmark test because it will be used for a sea waves

energy converter where thermal constraints are similar to those of HEPEs.

2.1 Experimental characterization

The test bench consists of three power resistors to provide heat input, a Teflon-Polystyrene insulator box to maximize heat transfer towards the cold plate, and the instrumentation to measure flow rate and temperatures (Figures 2, 3).

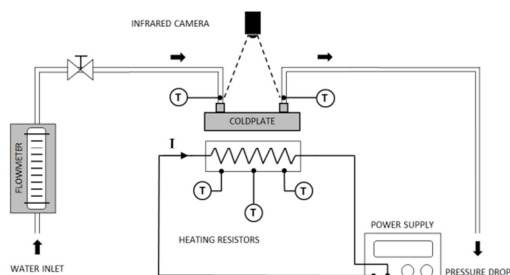


Figure 2. Schematic of the test bench.

Besides electrical quantities, the measured parameters include inlet and outlet cooling water temperatures and the cold plate surface thermal map, obtained by two dedicated thermocouples in the connection ducts and an infrared camera respectively. In addition, three thermocouples are inserted in the thermal insulation box to monitor the resistor temperatures and prevent overheating (Figure 4).

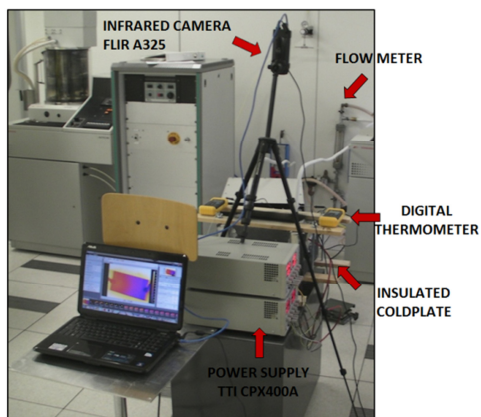


Figure 3. Photograph of the test bench.

Various experimental runs were carried out changing inlet delivery and electric power in resistors. For a typical experimental run, the flow rate was adjusted to a desired level. After reaching a steady flow rate, a desired heater

power was applied. The data were collected when steady-state conditions were achieved. The steady-state conditions were assumed to be reached when the changes of the maximum temperature reading was less than 0.2 °C within 25 min.

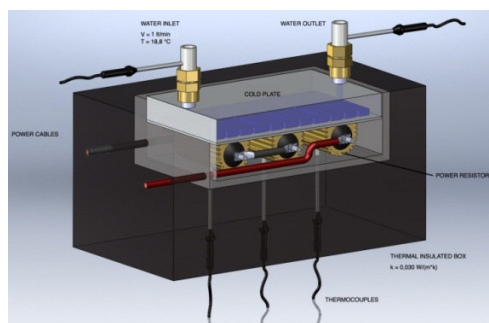


Figure 4. Section view of the cold plate with heating resistors, insulator box and thermocouples.

2.2 Numerical Analysis

The detailed flow field and heat transfer inside the cold plate are investigated by Computational Fluid Dynamics (CFD) method, which combines the governing equations for the fluid flow with the heat convection in fluid and the heat transfer in solid equations. The relative small inlet flow rate of the studied case (around 1 l/min) suggests water laminar flow. This preliminary hypothesis was made using Reynolds number and was confirmed by the simulation results. More details about the model are shown in Figure 5.

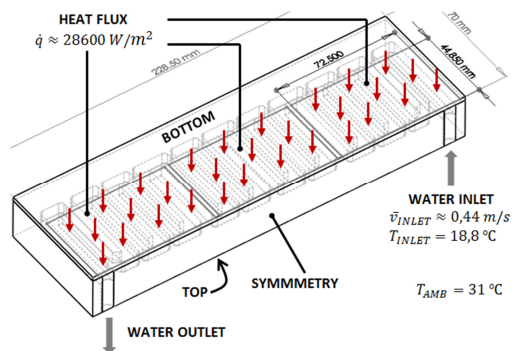


Figure 5. 3D FEM of the cold plate for benchmarking.

The uniform heat flux on resistors contact surface is equivalent to their total dissipated power (560 W). The lateral surfaces were set as

adiabatic, while on the top surface has been considered the natural horizontal air convection.

Using the *Conjugate Heat Transfer Module* for the FEM in Figure 5 we obtained the results of Figure 6.

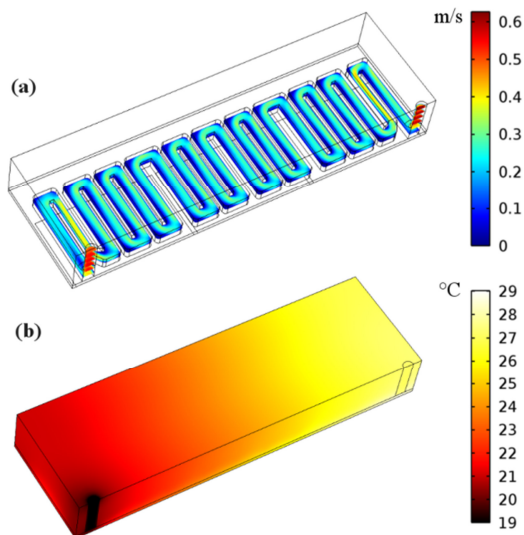


Figure 6. Steady state conjugate heat transfer simulation of the cold plate: velocity magnitude at the middle of water path (a) and temperature map across the heat sink (b).

The same model has been run with different values of dissipated power and inlet flow rates, as made for measurements.

2.3 Simulations vs. measurements

The only data available for model validation are the punctual temperatures measured by the two thermocouples at the coolant inlet and outlet, and the temperature across the top surface estimated by using infrared thermography.

For simplicity we only report the results obtained by the run with dissipated power of 560 W. In this case the maximum temperature of the cold plate is around 30 °C and the one over the resistors (60 °C measured) is much lower than their maximum operating temperature (120 °C).

As can be seen from Figure 7, the temperature and its gradient for measurements and simulations are almost the same. This can be better appreciated in the graph in Figure 8, which shows the temperatures along the symmetry line on the cold plate top surface. The matching of simulations with experimental results is also good, for water temperatures at the inlet and outlet (see Table 1).

Comparisons of runs made at different conditions gave the same feedbacks.

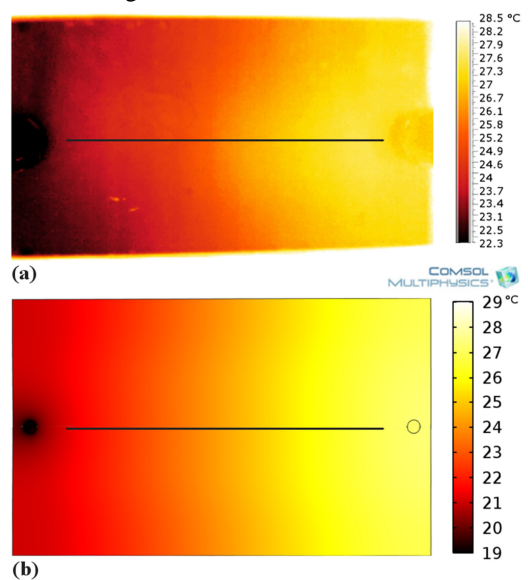


Figure 7. Surface temperature: comparison between IR measures (a) and COMSOL simulation results (b).

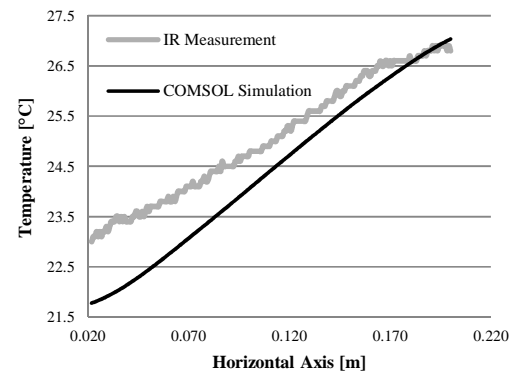


Figure 8. Surface temperature along the black horizontal lines of Figure 7.

	T_{inlet}	T_{outlet}	ΔT
Thermocouple	18.8 °C	24.8 °C	6.0 °C
COMSOL	18.8 °C	25.6 °C	6.8 °C

Table 1. Inlet and outlet water temperatures.

3. Simulation of a DC/DC power converter with an “U-shaped” cold plate

Once the modeling procedure for the cold plate was validated, we used it to simulate the

thermal behavior of the DC/DC power converter prototype for the ATLAS experiment.

This converter is designed to deliver a maximum power of 1.5 kW and it is fixed on an aluminum heat sink with a simple U-shaped water path inside (Figure 9).

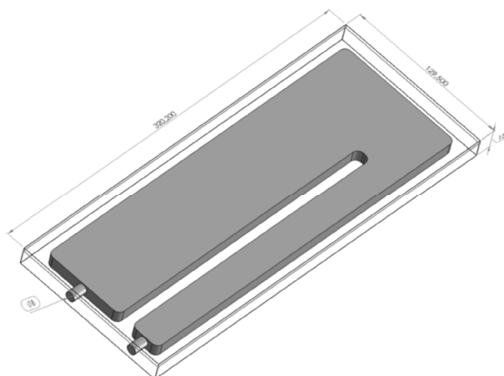


Figure 9. “U-shaped” aluminum cold plate of the DC/DC converter prototype.

Obviously, the DC/DC converter prototype is composed by a lot of electronic devices for power conversion and its control. Hence the whole system has a highly complex geometry [2]. Accurate studies would require detailed representation, but this would imply very high Degrees Of Freedom (DOF) for the FE model, and consequently big computational effort. One way to circumvent this problem is to take into account only the devices where heat generation is significant, and to use simplified geometries or models of the single components embedded in the system [3].

This part of the work aims to assess if this kind of FE analysis can be accurate enough to evaluate heat exchange in the environment and the steady state maximum temperatures reached in the system components. For this reason the geometry of electronic system was drawn following the guidelines previously described, and once again simulations were validated with experimental data.

During measurements the power module operates at two different delivering powers: 1.2 kW and 1.5 kW. The dissipated power in these conditions are 240 W and 380 W respectively.

Simulation results of steady-state study for the prototype converter delivering 1.2 kW are shown in Figure 10.

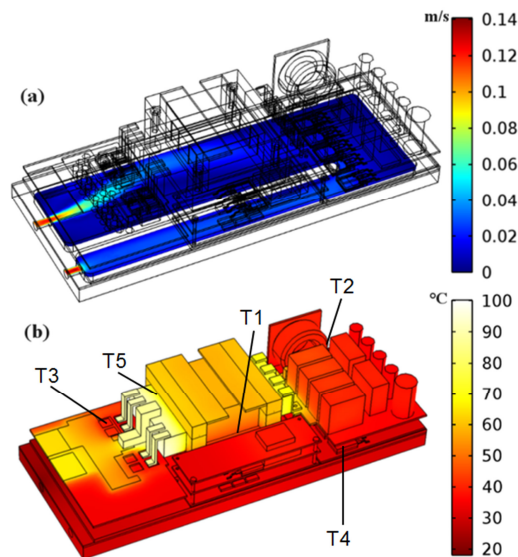


Figure 10. Steady state conjugate heat transfer simulation of the DC/DC power converter prototype (with “U-shaped” cold plate): velocity magnitude at the middle of water path (a) and surface temperature across the system (b), $P_d = 240$ W.

Comparing thermocouple and infrared temperature measurements with simulation results we observed a good match between them. Table 2 shows the temperatures in some significant points of the converter.

	Thermocouple	COMSOL
T1	35.1 °C	39.8 °C
T2	36.7 °C	37.3 °C
T3	37.5 °C	38.4 °C
T4	40.0 °C	39.1 °C
T5	77.2 °C	75.7 °C

Table 2. Punctual temperature comparison between values measured by thermocouples and results obtained from COMSOL simulation.

4. Cold plate optimization

The aluminum “U-shaped” cold plate used for the prototype is not an optimized solution with respect to all the application constraints that it has to satisfy. In particular, the following constraints have to be satisfied: inlet and outlet on the same short side; *cold plate thickness* = 15

mm; water path diameter = 5 mm; flow rate = 1,9 l/ min, maximum pressure drop = 350 mbar; $T_{inlet} = 18\text{ }^{\circ}\text{C}$; maximum $T_{outlet} = 25\text{ }^{\circ}\text{C}$.

The heat generation in the converter is not uniform, but as a first approximation it can be divided in four main regions where heating takes place: the planar transformer, the primary, the secondary and the auxiliary power supply. Then, considering only the cold plate, we model the inward heat flux from power electronics to the cold plate as four different uniform heat fluxes (see Figure 11, for a delivered power of 1.5 kW).

Starting from the model developed of the “U” cold plate, different topologies have been examined to search for the best one.

The solutions tested are shown in Figure 12. The idea is to enlarge as much as possible the heat exchanging surface area between solid and fluid. The solutions (a) and (b) are preferable when the pressure drop have to keep as lower as possible, while the other two maximize the heat transfer capability. Because of the high heat generation in the transformer, an asymmetric pattern such as (d), with the coldest part of the water just under the transformer, has been analyzed. Although the “double snake” is obviously the best solution for the total heat extraction, it is not immediate to evaluate if some

constraints, such as the maximum pressure drop or the maximum water temperature at the outlet, can be satisfied. For this task it is necessary to use the simulation approach.

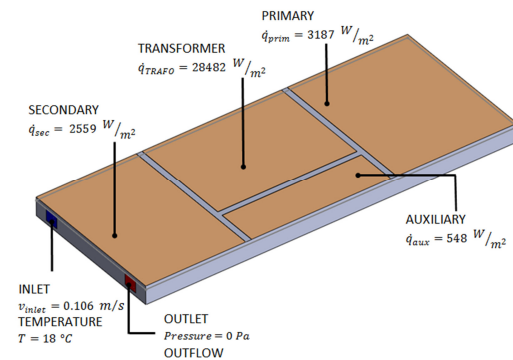


Figure 11. 3D FEM cold plates boundaries conditions, in case of a delivered power of 1.5 kW.

Simulation results for the described topologies are shown in Figure 13. As expected the temperatures on the surface connected to the electronics are lower in the “double snake” solution than in the others, although water outlet temperature is higher than the maximum allowed value, as can be seen in Table 3.

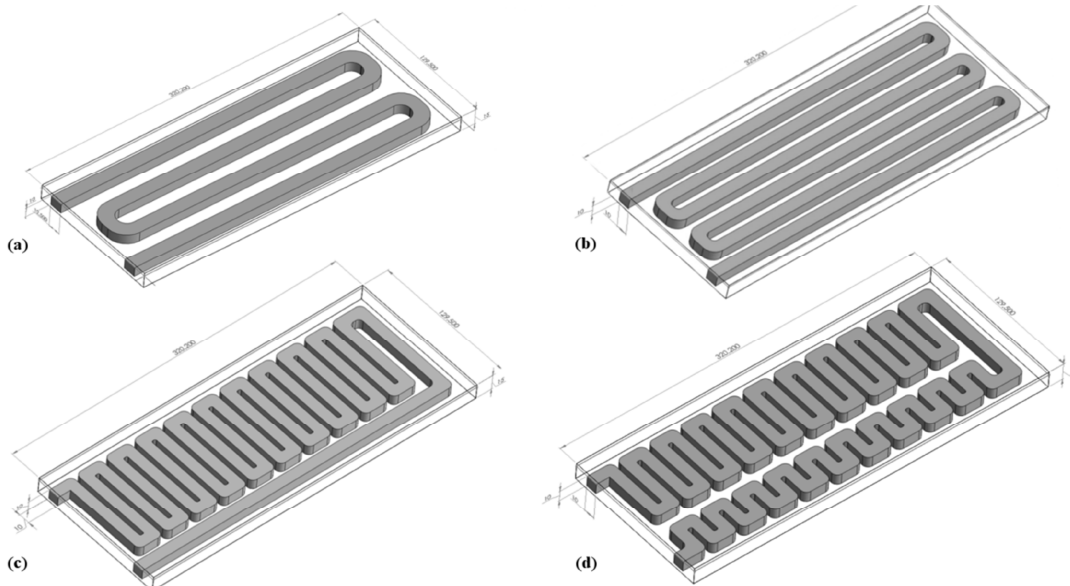


Figure 12. Different water channel topologies for the aluminum cold plate: (a) “four longitudinal paths”; (b) “seven longitudinal paths”; (c) “single snake”; (d) “double snakes”.

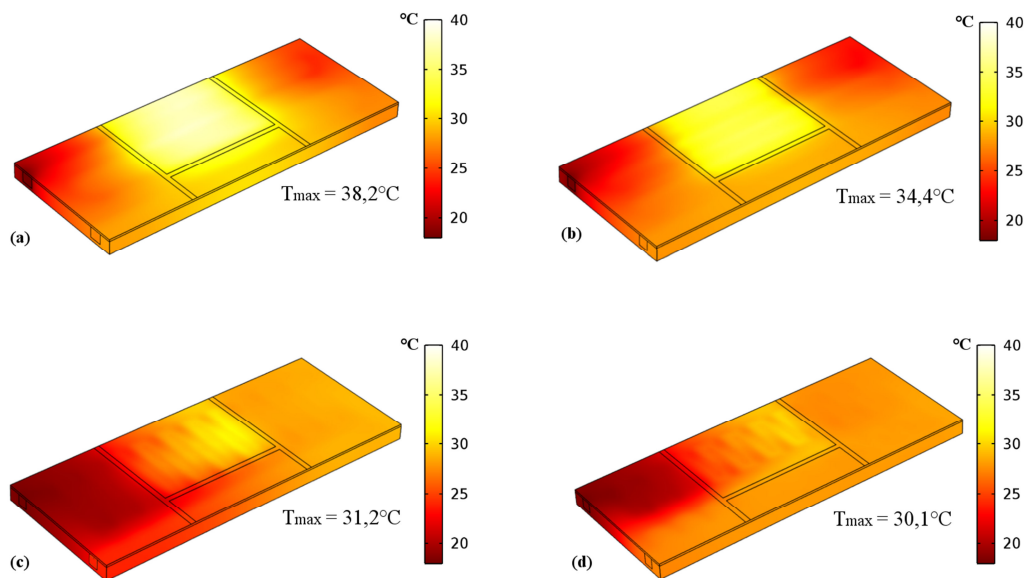


Figure 13. Steady state conjugate heat transfer simulation of the cold plates in Figure 12.

From simulation we examined how topology influenced the heat transfer. In particular we observed a sort of tradeoff between maximum water temperature at the outlet and maximum devices temperature.

Pattern	(a)	(b)	(c)	(d)
T_{outlet}	24.8 °C	27.4 °C	26.8 °C	27.2 °C

Table 3. Average temperature of water at the outlet for the different cold plate solutions.

Solution (a) is the one that satisfy all the constraints, but it is the less efficient in the heat extraction. Thus, it is necessary to verify if the temperatures of the electronics devices are lower than their maximum operating limits.

5. Simulations of power converter with cold plates

First of all, the DC/DC converter cooled by “four longitudinal paths” plate was simulated when the delivered power is 1.3 kW and 1.5 kW. In those cases the dissipated power is 280 W and 380 W respectively.

In Figure 14 the results of the water flow and the temperatures at the boundaries are shown. Here the maximum temperature is around 110 °C at the windings of the planar transformer. This is

a value near the maximum temperature for a reliable power module.

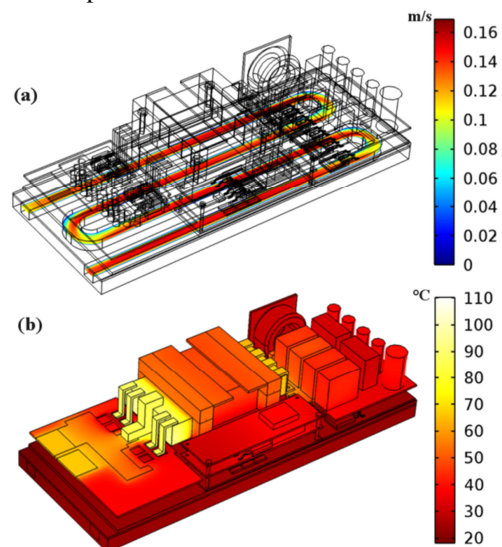


Figure 14. Simulation of the whole power converter using the cold plate with the “four longitudinal paths” ($P_d = 280$ W): (a) velocity field of the water at the middle of the duct; (b) thermal map.

Increasing the power at the maximum deliverable ($P_d = 380$ W), the maximum temperature is around 120 °C. It’s a value that cannot be tolerated in a power module which has to operate with high reliability.

These simulation results show that the maximum temperature of power converter fixed on the “four longitudinal paths” cold plate is approximately 15% lower than the one of the same electronics fixed on the “U-shaped” cold plate prototype. Water outlet temperature remain in the allowed range (24.8 °C) even in the worst case ($P_d = 380$ W).

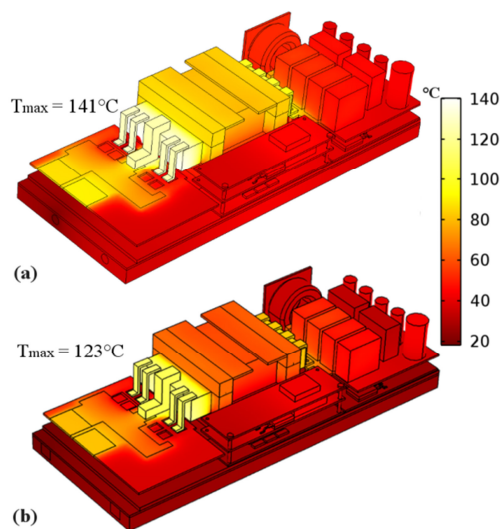


Figure 15. Thermal map of the whole converter: (a) with “U-shaped” cold plate; (b) with “four longitudinal paths” cold plate. The dissipated power is 380 W.

7. Conclusions

This work shows how a complex power converter with liquid cooling for numerical simulations can be modeled. The implemented simplified models solve the fluid dynamic problem fully coupled with the thermal problem. The approximations introduced to simplify the models without losing accuracy were validated with ad-hoc test bench and measurements. After validations the modeling method has been used to design the optimum cold plate for a power converter that has to operate with high reliability in hostile environments.

Some solutions of duct patterns in the cold plate were analyzed. The analysis showed that efficient heat removal of the cold plate cannot be applied to the current power module due to its efficiency: the power to dissipate for keeping the electronic components in it enough cold is too

much high for the constraints that the cold plate has to satisfy.

Further studies have to be done to improve the converter efficiency and to optimize the cold plate.

8. References

1. Aad G et al., The ATLAS experiment at the CERN Large Hadron Collider, *Journal of Instrumentation*, Vol. 3 (2008)
2. M. Alderighi et al., Power converters for future LHC experiments, *Journal of Instrumentation*, Vol. 7 (2012)
3. P. Cova, N. Delmonte, R. Menozzi, Thermal characterization and modeling of power hybrid converters, *Microelectronic Reliability*, Vol. 46, pp. 1760-1765 (2006)