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Thermal modeling and characterization of power converters for LHC power supplies

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Abstract **-** Power supplies for LHC experiments require DC-DC power converters able to work in very hostile environment. The APOLLO collaboration, funded by the Italian Istituto Nazionale di Fisica Nucleare (INFN), aims to study dedicated topologies and to design, build and test demonstrators, developing the needed technology for the industrialization phase.
Besides the presence of radiation and magnetic fields, thermal specifications are particularly stringent in the working environment. In order to have the wanted features in terms of reliability and availability during the experimental activity, these power electronics circuits must be cooled by specifically designed water heat sinks, and an accurate thermal design is mandatory in order to guarantee safe and reliable operation.
In this paper thermal characterization is used for tuning a coupled thermo-fluid-dynamic 3D numerical model, for both the water heat sink and the whole system. Based on this model an optimized water heat sink was designed and fabricated. Thermal characterization of the power converter demonstrator in different operating conditions shows good agreement with simulation results.

I. Introduction

The Large Hadron Collider (LHC) is, nowadays, the world's largest and highest-energy particle operative accelerator, built by the European Organization for Nuclear Research (CERN). The LHC can be used in order to verify the predictions of different theories of particle physics and high-energy physics with particular attention to prove the existence of both the Higgs boson and the large family of new particles predicted by super-symmetric theories. The aforementioned collider extends the frontiers of particle physics thanks to its high energy and luminosity [1]. Inside it, in fact, the high interaction rates, radiation doses, particle multiplicities and energies, push the features of the utilized instrumentation and measurement equipment to new standards that are necessary to consider during the design phase. This is particularly true for both the detector ATLAS (A Toroidal LHC ApparatuS) and every device involved in the experiments [1]. In fact, electronics converters employed in power supplies for the LHC ATLAS experiment operate in hostile environment, due to the simultaneous presence of radiation and high static magnetic field, which impose severe design constraints. Moreover, the power supply has to be quasi-adiabatic, due to the proximity of very sensitive detection circuitry, and this requirement implies water cooling and very stringent thermal constraints [2, 3]. Thermal management represents the key issue in designing these converters and accurate thermal modeling is mandatory to maximize the RAMS performances (Reliability, Availability, Maintainability and Safety) [4, 5].
All the RAMS requirements are relevant to this case. In fact, reliability is defined as the ability of an item to perform a required function under given conditions for a given time interval, and, quantitatively, assuming that the item is capable of carrying out its required function at the beginning of a specific time interval, reliability is the probability of failure-free performance over the specified timeframe, under specified conditions [4]. Moreover, availability is the ability to perform a required function under given conditions at a given time instant or over a given time interval, assuming that the required external resources are provided [4]. Maintainability is the ability of an item under given condition of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources [4]. Finally, it is important to underline that also in this kind of applications, safety (qualitatively defined as the absence of catastrophic consequences on the users and the environment in case of malfunction) is mandatory. It is very important, at this point, to highlight that for these devices maintenance must be correctly scheduled in order to be in compliance with the experimental activity. At this aim, the maximization of the parameters connected to the reliability, availability and safety must be taken into account. For example, some kinds of redundancies are mandatory. Diagnostic-on-board tools can be, obviously, very useful in these kinds of

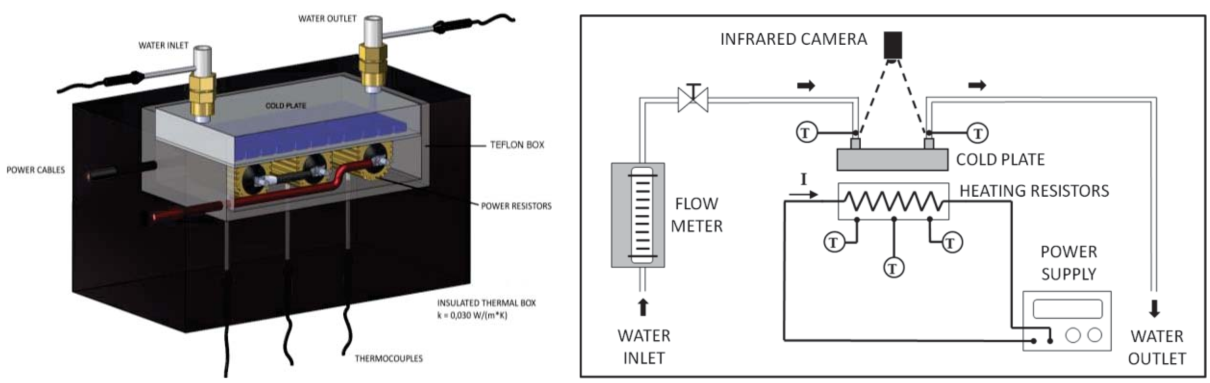
applications. In fact, only appropriate diagnostic allows to address the problem of maintenance between two different policies. In the first policy, called corrective maintenance (CM), the maintenance is performed after a system failure. In the second one, called preventive maintenance (PM), maintenance is performed before a system failure [6, 7]. In order to follows this second approach, policy diagnostic tools are necessary as aforementioned. Not least, the thermal behavior of the system has to be kept under control, in order to prevent components degradation. An accurate thermal modeling may be very useful not only for thermal sizing, but also to identify the most critical components and find the most appropriate placement of thermal sensors for diagnostics.
In the present work accurate thermal modeling of the water heat sink is addressed, in order to design an optimized water path for a specific converter which will be possibly adopted in the next ATLAS power supplies. A description of the developed 1.5 kW DC-DC converter can be found in [8] and a detailed thermal model of it, with identification of the main heating component is reported in [9]. For *ad-hoc* water heat sink developing, a fluid-dynamic model of the water path has to be coupled with thermal models of both liquid and solid domains of the heat sink. This is not an obvious task, since some parameters are known with large uncertainty and the models have to be tuned experimentally. Section II describes the procedure followed for setting and tuning such models on the basis of thermal characterization of a known heat sink prototype. Moreover the thermal behavior of the whole converter mounted on the heat sink has to be simulated. Due to the complexity of the converter structure, which is made by many heating components, an established simplifying procedure [10] has been followed to obtain an effective reduced converter thermal model.
On the basis of the numerical thermo-fluid-dynamic model the specific water heat sink was designed (as described in Section III) and fabricated. Section IV shows the good agreement between thermal characterization of the whole system and simulation results. Discussion concerning results and further considerations will be given in Section V. Finally, conclusions are given in Section VI.

II. Validation of thermo-fluid-dynamic FE model

A known water heat sink, made by milled aluminum, was used as a reference for thermo-fluid-dynamic 3D numerical model tuning. The thermal performances of this cooling device were characterized at various liquid flow rates and compared with simulation results in the same operating conditions.

A. Experimental set-up

In the application the converter must be thermally insulated from the surrounding electronic detection circuitry, operating in quasi-adiabatic condition, then almost all the heat dissipated by electronics must be collected by the heat sink and extracted by the water. For this reason a test bench was built, in which all the surfaces of the heat sink, except the back side, used for measurements, were thermally insulated by a Teflon-polystyrene box, as illustrated in Figure 1.a. Figure 1.b shows a schematic view of the measurement setup.



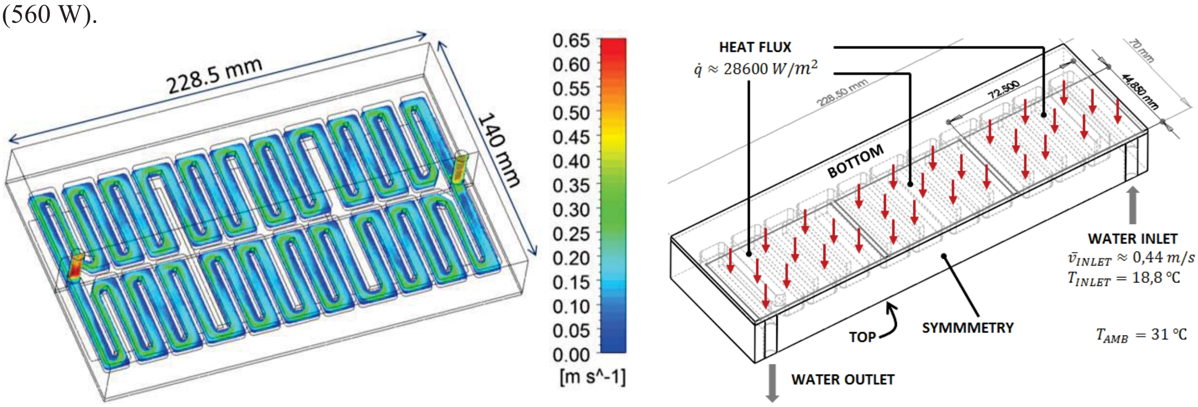
(a) (b)

Figure 1. (a) 3D model of experimental set-up for numerical model tuning; (b) schematic of the test bench.

Three power resistors provide heat input to the heat sink. Power was regulated by a couple of TTI CPX400A power supplies. Measured parameters include inlet and outlet cooling water temperatures and the heat sink surface thermal map, obtained by two dedicated thermocouples in the connection ducts and an infrared camera (FLIR A325) respectively. In addition, three thermocouples are inserted in the thermal insulation box to monitor the resistor temperatures and prevent overheating. All the thermocouples were *k*-type. Tests were carried out by changing inlet delivery and electric power in resistors. For each value of flow rate and heating power the data were collected after steady-state conditions were achieved. The steady-state conditions were assumed to be reached when the change of the maximum temperature reading was less than 0.2 °C within 25 min.

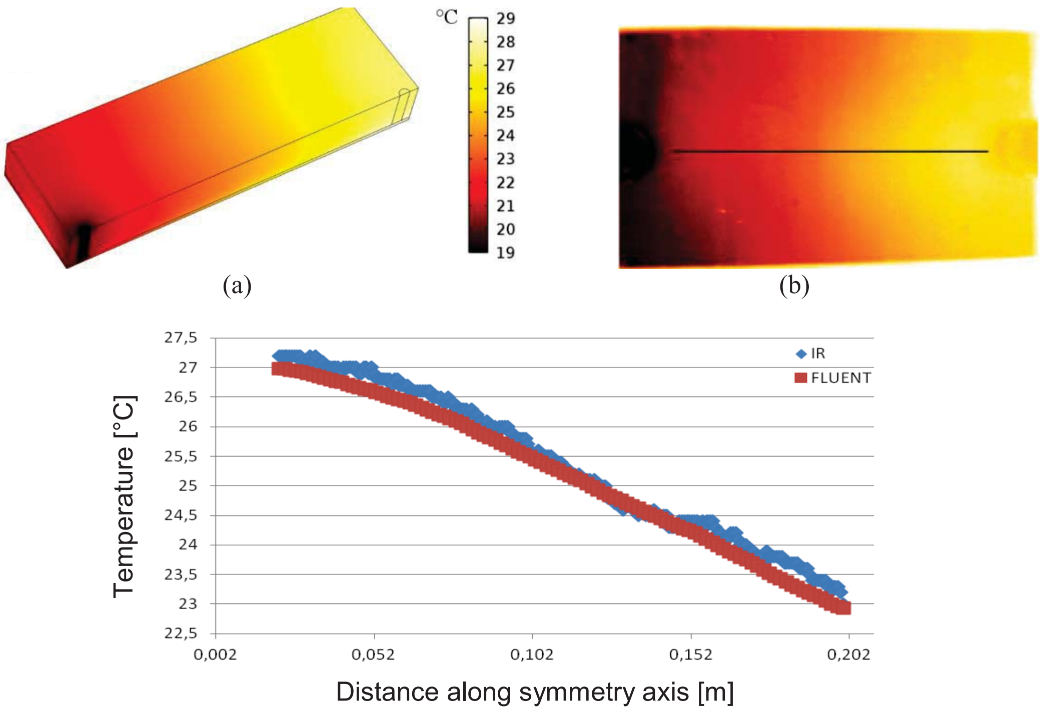
B. Numerical model tuning

Figure 2.a shows the geometry of the reference model and the water velocity field inside. We used and compared two commercial software packages: COMSOL Multiphysics and ANSYS-Fluent. The detailed flow field and heat transfer inside the heat sink 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 [11]. 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 simulation results. Figure 2.b shows some of the parameters set in the model (due to the symmetry, only half of the structure was modeled). The uniform heat flux on resistors contact surface is equivalent to their total dissipated power (560 W).



(a) (b)

Figure 2. (a) Geometry of the reference water heat sink; (b) FE model, with indication of boundary conditions.



(c)

Figure 3. (a) Steady state simulated thermal map (COMSOL) for the reference heat sink (half structure) at operating conditions of Figure 2b; (b) IR temperature map; (c) measured and simulated (ANSYS) heat sink surface temperature along the black horizontal lines of Figure 3.b.

The lateral surfaces were set as adiabatic, while on the top surface has been considered the natural horizontal air convection.
Previous Figure 3 shows an example of simulation results (COMSOL) for a dissipated power of 560 W and a delivery of 1.3 l/min. Maximum temperature was around 30 °C on the heat sink and 60 °C on resistors.
The temperatures measured by the two thermocouples at the coolant inlet and outlet, and the temperature across the top surface estimated by infrared thermography were used for model validation. As fitting parameter the heat convection coefficient h at the air-exposed boundary were set. This parameter can be estimated by *rule of thumb*, but it is very hard to evaluate its actual value because it depends by many others parameters and/or operating conditions, so, to obtain good results from simulations, we can test different values to find the one that allows to obtain the best fit. Here, h was set to around 7 W/(m^{2}K), a typical value for natural air convection. By comparing the simulated thermal map of Figure 3.a with Figure 3.b, which reports the corresponding IR measurement, a good agreement appears. This can be better appreciated in Figure 3.c, which shows the comparison between temperatures along the symmetry line on the heat sink top surface. The matching is also good for water temperatures at the inlet (both 18.8 °C) and outlet (measurement: 24.8 °C, ANSYS simulation: 25.1 °C).

III. Optimized heat sink design

The developed model was exploited to design a specific water heat sink, able to comply with constraints, which were: inlet and outlet on the same short side; thickness 15 mm, water path diameter 5 mm; flow rate 0.63 l/min, maximum pressure drop 350 mbar; T_{inlet} = 18 °C; maximum T_{outlet} = 25 °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 region, the primary and the secondary regions and the auxiliary power supply region [5]. In order to easily evaluate the performance of different water paths we simulated the heat sink alone, by modeling the inward heat flux from power electronics as four different uniform heat fluxes, as shown in Figure 4 for delivered power P_{out} = 1.5 kW.
With these boundary conditions different topologies were examined in order to enlarge as much as possible the heat exchanging surface area between solid and fluid in the region were the input heat is higher. The chosen design is illustrated in Figure 5.a.

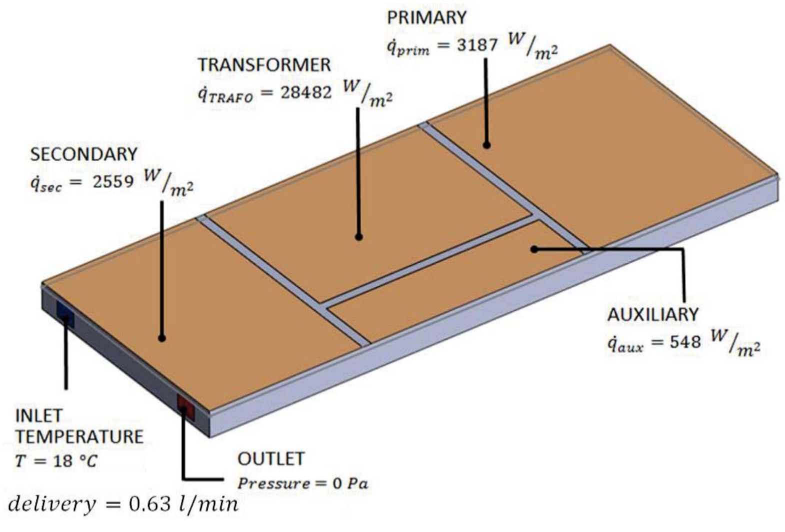
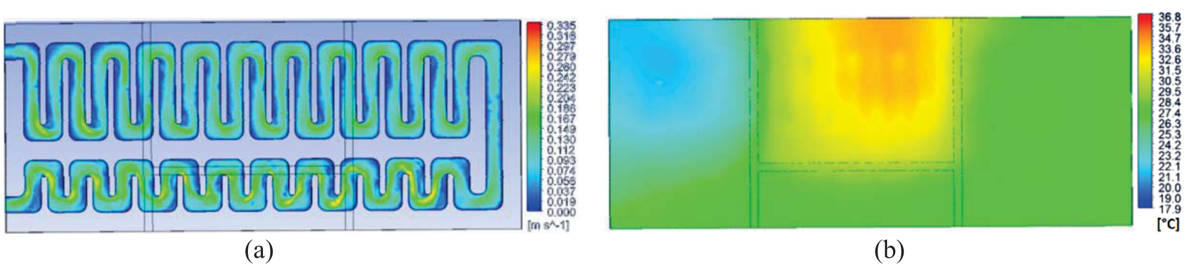


Figure 4. Boundary conditions on the heat sink surface in contact with the converter, in case of P_{out} = 1.5 kW.



(a) (b)

Figure 5. Water velocity field in the designed heat sink (a) and thermal map simulated at the surface in contact with the power converter operating at P_{out} = 1.5 kW (b).

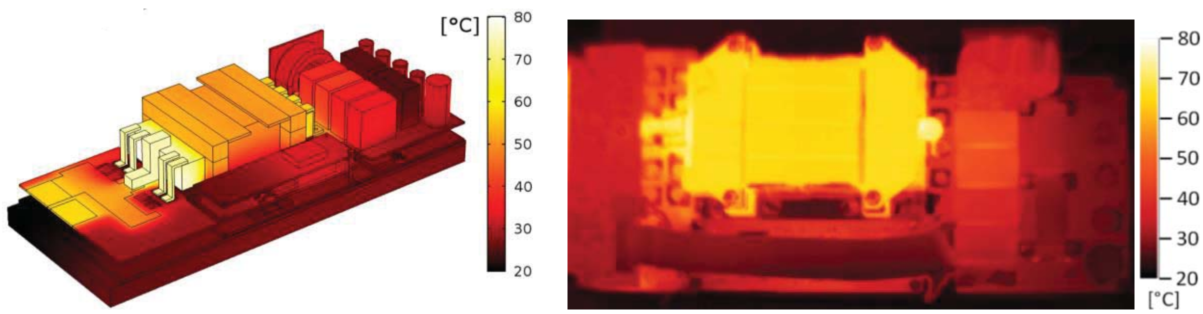
Finally, Figure 5.b shows the thermal map simulated with this structure at the surface in contact with the power converter delivering 1.5 kW.

IV. Full converter modeling and characterization

The power converter was modeled by the simplified blocks method [9, 10] and the thermal behavior of the assembly made by the converter mounted on the designed heat sink was simulated. The heat sink was fabricated by milling an aluminum plate and brazing on it the aluminum cover plate. The converter was mounted on the heat sink ensuring optimal thermal contact by a thin layer of thermal paste, and uniform pressure was guaranteed by screws. The whole assembly was tested at different operating conditions by a test bench able to fix and measure all the operational parameters. In particular:

- Differential inlet/outlet water temperature by means of a thermometer based on *k*-type thermocouples (0.1 °C of resolution) at the input and at the output of the heat sink. The minimum differential measured temperature was 1.7 °C and the maximum differential measured temperature was 2.7 °C. Mean value during the experimental activity was about 2.2 °C. Both the water temperature measured during the tests and the differential inlet/outlet water temperature are in compliance with the constraints above reported: T_{inlet} = 18 °C; maximum T_{outlet} = 25 °C.
- Differential inlet/outlet water pressure by means of two pressure sensors type PSE560-02 from SMC installed near the input and the output of the heat sink. The pressure is measured using an interface type PSE200-MA4C from SMC (+/- 0.5% F.S.). The differential inlet/outlet water pressure during the experimental activity was stable at 210 mbar. This value is in compliance with the specification aforementioned. In fact, a maximum pressure drop of 350 mbar is allowed.
- Water flux by a water digital flux-meter type PF3W704-F03-BTN-M from SMC. The nominal range of the adopted sensor is 0.5 - 4 l/m (+/- 3% F.S.). During the experimental activity the reading of the water flux was stable at a mean value of 0.6 l/m. Also in this case, the measured value complies with constraints concerning water flow rate 0.63 l/min, as aforementioned.
- Temperature map by a FLIR A325 infrared thermo-camera. All the reflecting surfaces were painted black, in order to obtain an almost homogeneous emission coefficient.
- Temperature of the most heating component by means of *k*-type thermocouples and PC-driven switching unit.

Figure 7 shows, as an example, the comparison between simulation and measurement in the case of converter delivering P_{out} = 1.2 kW.



(a) (b)

Figure 7. Thermal map of the power converter mounted on the designed heat sink at operating conditions: P_{out} = 1.2 kW, T_{inlet} = 18 °C, T_{amb} = 21 °C. (a) Simulation; (b) IR measurement.

V. Discussion

Complex systems operating inside the LHC must comply with very stringent RAMS requirements. One of the key issues is the thermal behavior of electronics converters in power supplies.

An accurate thermal modeling, accounting for conduction, air convection and fluid-dynamic heat transport, drives to the knowledge of the most critical components and conditions in the system, allowing the design of optimized water heat-sink.

Moreover, we asserted the importance of performing preventive diagnostics. This is true even up the design stage, to which it requires to contemplate the identification of the most appropriate regions were positioning temperature sensors able to detect component degradation at the early stage. In this way, with the support of the developed thermal model, it is possible to identify and localize thermal and/or thermo-mechanical degradation

modes, and it is possible to take proper corrective actions and even to substitute power modules which show component degradation, when maintenance interruptions are scheduled.
It is important to highlight that predictive diagnostics can also put out design errors or weaknesses of the design. For example, the planar transformer proved to be the weakest point only after the thermo-graphic analysis and simulation of the complete main converter. In fact, in the design phase with electronic simulation tools (such as SPICE) it is not always possible to put in full light the aspects of thermal dissipation. Finally, it is important to highlight that predictive diagnostics can therefore lead to design review with significant savings in the prototyping phase.

V. Conclusions

A coupled thermo-fluid-dynamic 3D model of a water heat sink for power electronic converters has been developed and tuned by thermal characterization of a known prototype. The model was used for designing a suitable solution for a specific complex DC-DC converter for application in LHC future experiment, with very stringent thermal constraints. The heat sink was fabricated and thermal measurements performed on the converter mounted on it show a good agreement with thermo-fluid-dynamic simulations of the whole assembly. Finally, both diagnostic aspects and maintenance strategies have been also discussed.

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