Power Electronics High Performance Air-Cooled Heat Sinks Integrating Graphite Based Materials

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ABSTRACT

The thermal management of the power electronics cooling in the aircraft is getting more attention in the recent years due to the progressive implementation of electrical systems, especially in the framework of the more electrical aircraft, one of Clean Sky framework research activities to allow Europe to lead the transition to more environmental friendly aircraft in the future. The reference innovative trend in the cooling of power electronics and other semiconductor devices has been to migrate from air cooled solutions to liquid cooled or two-phase flow solutions, as these being able to reach higher levels of heat transfer density and keep electronics temperatures within the required limits. However, in the context of new wide-bandgap semiconductor materials (GaN, SiC) that withstand higher operating temperatures with reduced losses, the use of air cooling is attracting again interest, as a potential candidate to reduce the complexity of thermal management systems, and indirectly their weight and cost. In this regard, the consortium of the Clean Sky 2 project ICOPE has been working in the development of new concepts of air cooled heat sinks that incorporate advanced thermal materials such as Annealed Pyrolytic Graphite (APG) and Metal Matrix Composites (MMC) (Aluminium Graphite (ALG)).The project has evolved from pre-design steps to identify potential design candidates towards a final design with the support of CFD simulations and engineering assessment. Different versions of heat sink incorporating different combinations of the referred materials have been manufactured and successfully tested. A first loop of prototypes, called Stage A, implement APG, while a second loop of prototypes (Stage B) integrate APG and MMC in different interactions. This paper is conceived as a summary of the project developments and results at heat sink level, presenting the overall concept, the materials involved, and the experimental and numerical results obtained, which achieve the expected performances in terms of heat transfer, pressure drop and weight. The outcome of these results can suggest to reconsider the power electronics cooling design in other applications outside the aircraft sector, for example within Power Conversion applications or automotive field.

1. INTRODUCTION

The topic of power electronics cooling is attracting more attention in the recent years due to the progressive implementation of electrical systems, related to the strong market expansion of fields like renewable energy and electric vehicles. For the latter topic, this includes the more electrical aircraft concept, one of Clean Sky framework (aeronautic section of European H2020 research programme) important research activities, where it is included the ICOPE project.

The reference innovative trend in the cooling of power electronics and other semiconductor devices has been to migrate from air cooled solutions to liquid cooled or two-phase flow solutions, as these are able to reach higher levels of heat transfer density and keep electronics temperatures within the required limits. However, coming from advances in the power semiconductors field, by the use of high-temperature and more efficient materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN), the thermal management strategy could take back into consideration the implementation of air cooled solutions (Waye, 2016; Matallana et al., 2019). If feasible, they are expected to reduce the complexity of the cooling solutions compared to liquid or two-phase flow devices, while also adding some benefits in terms of weight/volume, cost, reliability/maintenance and flexibility (Morioka et al., 2014; Waye, 2016).

The key strategic aspect is if we can take profit of this opportunity with common air-cooled heat sinks (not probable), or if we can only achieve the required performance (power to mass ratio) by developing innovative heat sinks using the most advanced materials and technologies (Tong, 2011; Wang et al., 2012; Wang, 2017). In this sense, two different high-tech carbonaceous materials were identified by the project participants as promising technological bricks, Annealed Pyrolytic Graphite (APG) and Metal Matrix Composites (MMC). APG is basically a very advanced heat spreader material, having in-plane conductivity of the order of 1700 W/mK, which is intended to spread the heat coming from the Power Electronic (PE) modules into a wider heat sink primary surface, then achieving good temperature values at fin bases, maximizing the air cooling capacity with the minimum weight. On the other hand, graphite/aluminium composites were chosen as the MMC of choice for the project, as they exhibit thermal conductivities in the range of Al (or higher for anisotropic alternatives), with less weight (about 20% less), and much better thermal inertia and expansion behavior (coefficient of thermal expansion (CTE) much closer to that of PE modules).

This paper is a summary of the project contributions at heat sink level, presenting the main aspects of the mentioned research in the different tasks, from the design of different alternatives, to their manufacture and testing. The results show the benefits of the integration of the new materials in comparison to an all aluminium benchmark unit.

2. HEAT SINK DESIGN

The use of air as a cooling medium with intrinsic very low thermal performance implies the necessity to increase the airside heat transfer surface (typically by implementing secondary surface as fins) and/or the heat transfer coefficient (modifying the surfaces morphology with louvers, waviness, etc.), in order to reduce the airside thermal resistance.

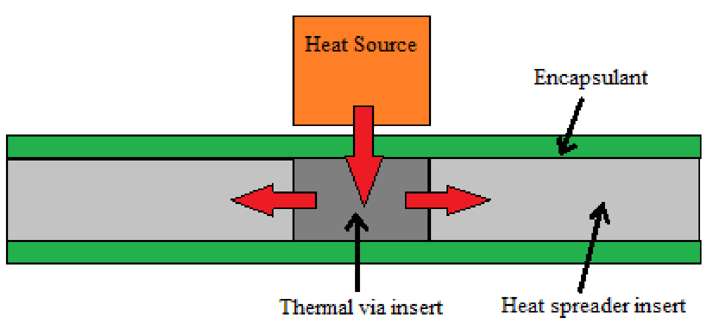

Figure 1: Heat sink base concept combining materials and functionalities.

In the particular application of electronic components cooling, there is an additional aspect to take into account in comparison to other heat exchangers, related to the fact that the heat dissipation is concentrated at the chips location.

This means that the primary surface changes its heat transfer topology completely, shifting from transversal heat transfer in most heat exchangers (from one fluid to the other crossing the primary surface of tubes/plates), towards a heat spreading scenario from the source to the rest of primary surface in the electronics cooling. In other words, the heat sink base is already introducing a thermal resistance (and a temperature change) before reaching the fins base, therefore acting as a primary fin.

Under such topology, if a high performance innovative air-cooled heat sink is to be generated, it should address ways to improve the heat sink base thermal behaviour, minimizing its thermal resistance to assure the effective use of secondary fins. The concept introduced in this paper is summarized in Figure 1, where a primary surface (heat sink base) section is depicted. The heat sink base is mainly enhanced by the implementation of a planar heat spreading insert, that would reduce the above mentioned thermal resistance towards the edges and fin bases. The encapsulant or parent material is kept for mechanical and integration purposes. As the planar spreading inserts typically suffer from low transverse conductivity, the design is complemented by the introduction of a thermal via insert below the heat source to facilitate the heat transfer from the source into the planar insert.

The innovative identified heat sink designs have been materialized by the incorporation of two main materials, Annealed Pyrolytic Graphite and Metal Matrix Composites, specially suited for the purposes introduced in the last paragraph, both for inserts or encapsulants. They are described in more detail in the following subsections.

2.1 Annealed Pyrolytic Graphite description

Annealed Pyrolytic Graphite (APG) is a graphite material of outstanding thermal properties, obtained after a complex procedure that among others implies the use of a hot isostatic pressing (HIP) process. The graphite layer is not used on its own, but encapsulated to avoid oxidation of the graphite using a quite wide portfolio of encapsulant materials (aluminium, copper, magnesium, beryllium, kovar, copper-moly, copper-tungsten...) to suit mechanical requirements of the application. The APG is decoupled from the encapsulant (i.e. there is no bond). As observed in Figure 2, its thermal conductivity is outstanding in the main planar directions (1700 W/mK), but low in the normal direction (12 W/mK). As already introduced before, the APG layer is transversally perforated with some high thermal conductivity via to overcome the low normal-wise conductivity (Figure 1).

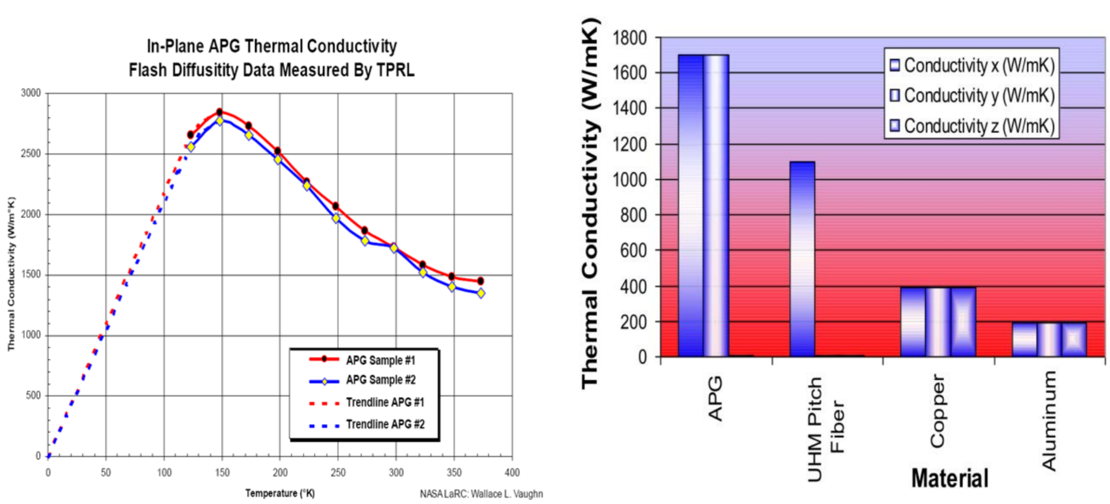

Figure 2: APG thermal conductivity. Left: temperature dependence of in-plane conductivity. Right: Anisotropic behaviour and comparison with other materials.

As seen, APG provides enhanced thermal features that make it a good candidate to develop a high performance heat sink. It also has other beneficial features:

- APG is lighter than most parent materials and so often provides a direct-weight benefit; of about 5% compared to Aluminium.
- It is a passive thermal solution and the thermal spreading is not affected by gravitational forces.

- It has a wide operational temperature from -123ºC (150K) to 180ºC (453 K) .
- Encapsulation material can be machined and permits standard metal finishes and processes.
- Can be CTE- matched to semi-conductor materials for direct attachment.
- Fully hermetic encapsulation, rugged and resistant to damage

2.2 Metal Matrix Composite description

The Metal Matrix Composites (MMC) have been selected as the second advanced material to be incorporated into the heat sink in order to improve its thermal performance. In particular, Aluminium Graphite (ALG) has been used, a combination that merge the key properties of aluminum and graphite components into one optimised MMC. These composite materials combine the low coefficient of thermal expansion and low density of graphite with the excellent thermal properties of aluminium to create an ideal thermal management solution for a wide range of high reliability applications. Aluminium Graphite is of particular interest for the power electronics industry, especially when there is a need for materials with a low thermal expansion. This most frequently comes to the fore in applications with large thermal gradients. In these, it is vital that all materials used in the electronic assembly show a similar thermal expansion. This significantly improves the reliability and the lifetime of the modules. Figure 3 compares the CTE of different materials used in the power electronics field, locating the ALGs with values much closer to those of semiconductor materials than other products like Al. Despite the strong change in internal microstructure generated by the presence of the graphite matrix, ALG maintains a very high thermal conductivity, equivalent or superior (in anisotropic designs) to that of aluminium. Regarding thermal diffusivity, ALG materials have outstanding properties in comparison to other materials, thanks to the graphite internal behaviour, with more than 50% higher values than usual materials. This allows ALG to remove heat faster than other materials, which is an important feature to smooth the possible peaks in electronics temperature due to fast transient operational/dissipation changes. One other significant advantage of Aluminium Graphite is it's low density, that allows a possible weight reduction potential from 14% compared to Al or Al alloys, 23% to other aluminium based MMCs (e.g. AlSiC), and up to 86% compared to copper based materials.

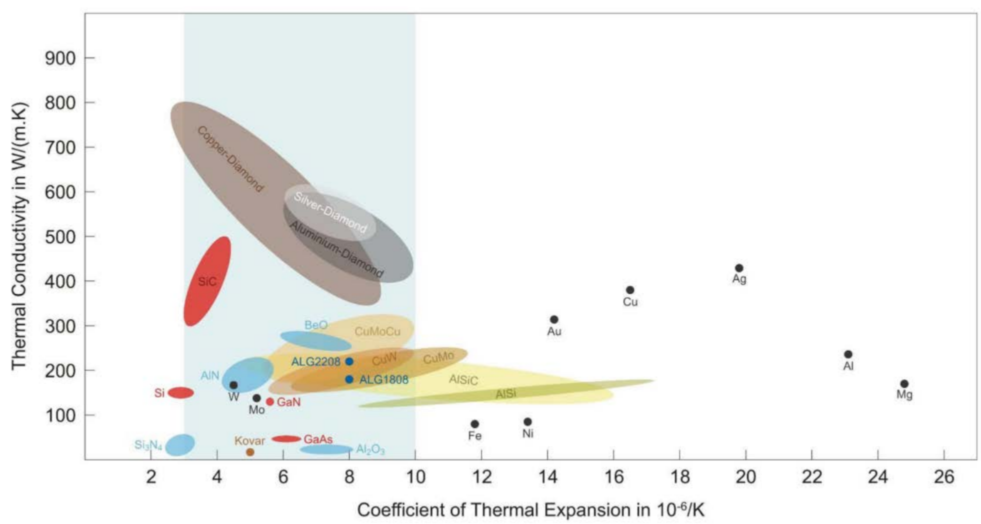

Figure 3: Coefficient of thermal expansion of ALG and comparison to other materials.

The individual parts required for each specific application are machined from the solid blocks. Compared to other MMC alternatives (AlSiC, CuMo, CuW, etc.) that require complex and time-consuming machining processes, ALG can readily be machined using common methods such as cutting, turning or milling. This allows for the production of customised parts with complex geometries and tight tolerances, creating a wide variety of parts like base plates, soldering jigs, heat sinks, heat spreaders, flanges or housings, etc. (Figure 4). Furthermore, these parts can then be plated with a range of metallisations from base metals such as nickel to precious metals such as gold or silver. In the current application, the ALG heat sink bases have been machined and nickel plated to allow the subsequent fin stack soldering. On the other hand, for other heat sink variants ALG inserts have also been machined with precision to be embedded in the ALG or aluminium bases.

Figure 4: ALG customized parts with complex geometries: base plates and coolers for power modules (left), heat sinks and housings for laser diodes (right).

2.3 Heat sink design and manufacturing

The work on the heat sink design has combined two main numerical analysis techniques: on one side pre-design extensive simulation and optimization using semi-analytical models (ε-NTU) coupled with a genetic algorithm mathematical engine has been carried out. Figure 5 shows an example of the design guidelines obtained with this approach: thermal dissipation (Q) vs pressure drop (ΔP) for different flow configurations or materials. The specific geometry values for each individual within the Pareto front (right) can be retrieved for any designer selected optimal point.

On the other hand, both at the pre-design steps for a set of concepts-geometries, and for in-depth design considering insertions and material combinations, specific simulations with industrial oriented CFD models have been carried out (Figure 6), considering the full 3D nature of the problem.

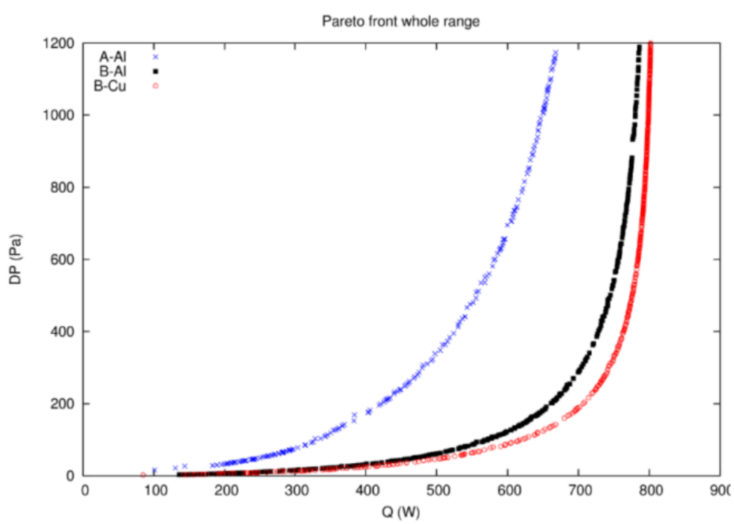

Figure 5: Numerical analysis of the heat sink by using the ε-NTU+GA tool.

The numerical design process has been applied iteratively to finally reach suitable solutions that meet all the requirements set in terms of maximum surface temperature, weight and pressure drop. This has resulted in four different heat sink bases, combining in different ways the conventional and advanced materials, as indicated in Table 1. After this decision, the process shifted to translate the design into a manufacturable unit. The main aspect in terms of heat sink base manufacturing has been the implications of combining for the first time APG and MMC inserts in a single unit, while also combining MMC encapsulant with APG inserts. The previous manufacturing processes have been combined and adapted to generate the new units.

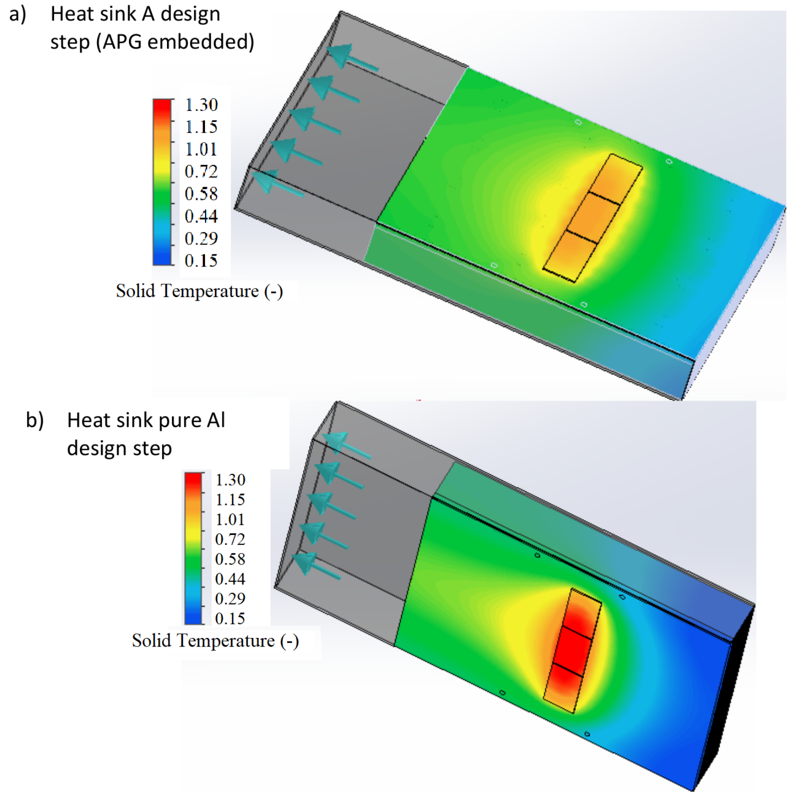

Figure 6: CFD analysis of a heat sink, with (top) and without (bottom) high conductivity insertions.

Table 1: Heat sink base identified material combinations

Heat sink	Encapsulant	Inserts
A	Al	APG
2B	MMC	APG
7B	MMC	APG + MMC-anisotropic
8B	Al	APG + MMC-anisotropic

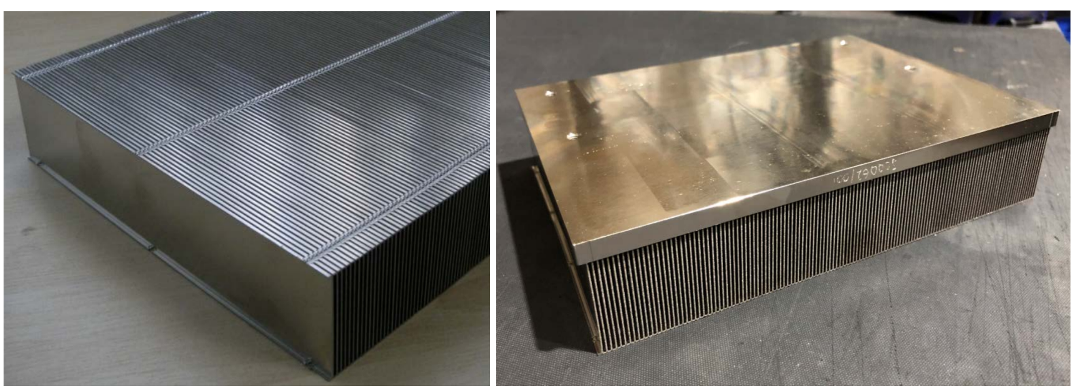

Figure 7: Left: Cassette fin stack. Right: Innovative heat sink manufactured, with heat sink base soldered with the cassette fin stack.

The other main aspect in terms of manufacturing has been finding a fin stack that complies with the expected fin spacing and fin thickness, while having a reasonable and cost-effective implementation. The solution found is based on cassette fins, which construction encloses the fins so that no additional containment of the air is required and there is minimal air leakage. The fin stack have then been soldered to the heat sink base to provide adequate thermal connection (Figure 7).

3. HEAT SINK EXPERIMENTAL SET-UP

The heat sinks have been tested in an experimental unit that has been prepared to produce the required specified environmental and operating conditions, in particular a capacity to deliver a fully developed flow up to 250g/s. Airflow is set using differential pressure measurements across a venturi within an airflow chamber. The chamber operation manual provides nozzle configurations for various flow ranges. Flow ranges are set by manually opening/sealing these nozzles. Flow then passes through a series of baffles, which creates an evenly distributed flow to the chamber outlet. Delivery fan speed can then be adjusted using a 4-20mA output controller to produce the desired differential pressure corresponding to a particular flow rate. The outlet allows for the fixation of bespoke discharge spigots for various test applications. A simple calculation must be conducted to determine the entrance length of each bespoke spigot to allow full redevelopment of flow before entering the product under test.

Figure 8 is a concept model of the heat sink test bench. Shown is a bespoke discharge spigot fixed to the air flow chamber outlet. The internal cross section of this spigot match that of the heat sink finned section. The heat sink fin stack is then settled in this spigot at a distance where flow is considered fully developed. Also shown in the same figure is a bespoke frame designed to support the spigot and heat sink.

The air velocity at the heat sink discharge has been measured by a turbine anemometer (with adequate small diameter to allow full immersion in the leaving airflow) at different spanwise positions to measure the outlet average velocity and to confirm an even flow distribution.

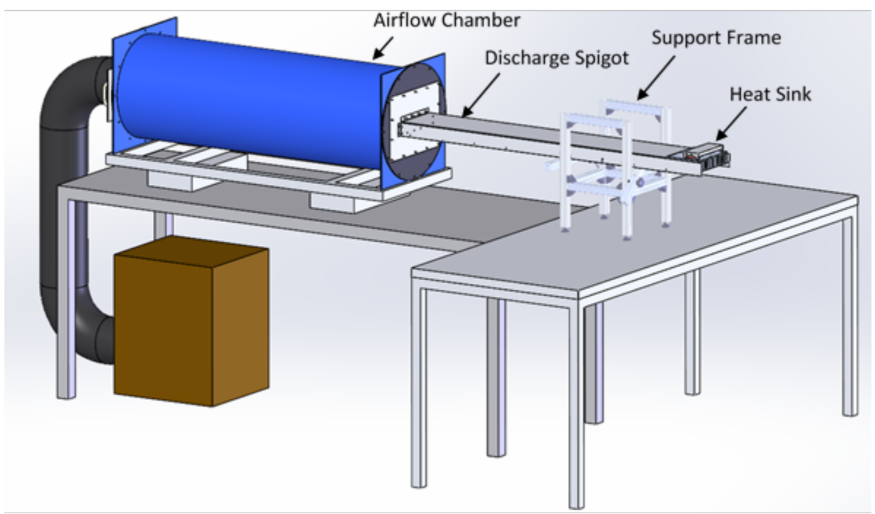

Figure 8: Heat sink test bench concept.

Figure 9 is an exploded view of the heater block fixation method to the heat sink. To guarantee accurate heater block positioning, an aluminium jig locates the copper block using the four fixing threads in the heat sink. A PTFE insulation plate separates the aluminium and copper to minimise heat losses into the aluminium jig. Insulation wool will be secured thoroughly around the discharge spigot, heat sink and heater block assembly during the tests to further minimise losses to atmosphere. The heater block has the exact contact surface with the heat sink as the corresponding power electronic module, while internally an electric resistance replicates its heat dissipation. The heat sink surface measurements have been done by placing several thermocouples on its surface, without embedding them in the material to avoid damage of the encapsulant. As indicated in Figure 10, the positions are distributed to capture the highest values near the heat

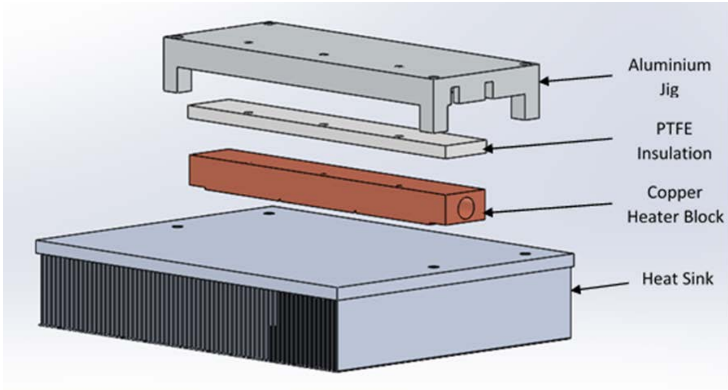

Figure 9: Heater block assembly.

source, and the edge temperatures in both stream-wise and span-wise directions.

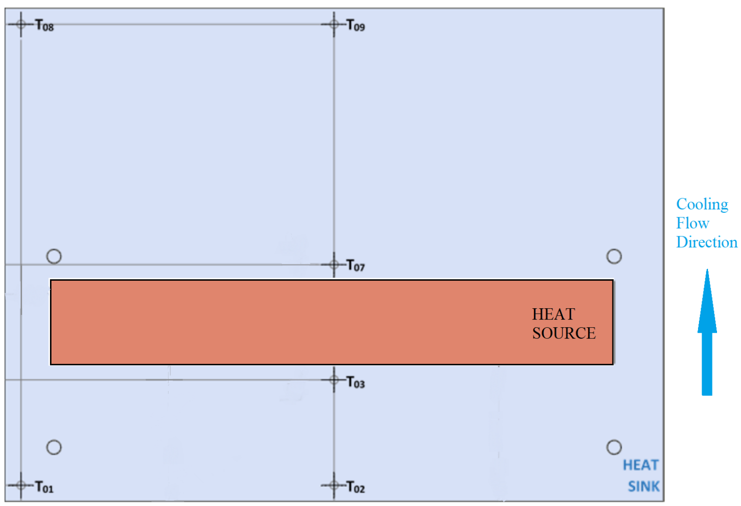

Figure 10: Heat sink surface thermocouples positioning.

4. SURFACE TEMPERATURE MEASUREMENT RESULTS

The heat sinks have been successfully manufactured (in their four versions) and tested. Table 2 summarizes the tests done at nominal conditions for Stage A and Stage B, with results in non-dimensional form ($T^* = (T - T_{air,in})/(T_{max,surf} - T_{air,in})$) to show clearly their relative position vs the maximum allowed surface temperature and to keep confidentiality. All units are analogous regarding the overall heat sink dimensions and fin stack geometry, thus only changing the materials of the heat sink base.

As can be seen they all improve the performance of the full aluminium benchmark heat sink, both in maximum temperature (T_{max}) and also in maximum temperature difference across the heat sink base (ΔT_{max}). T_{max} is reduced about 10 to 15%, and ΔT_{max}, although showing some scattering, is reduced up to more than 50%. This confirms, as already observed numerically in Figure 6, a lower temperature at the heat source location, and a more uniform temperature all along the heat sink base with the new innovative heat sink base.

Regarding Stage B, the tests have shown positive results on the thermal side, confirming a performance similar to Stage A considering the actual temperature measurements, but without the expected improvement inferred from the design simulations. On the other hand, the temperature results show some scattering, probably due to manufacturing

Table 2: Heat sink surface temperature measurements in steady state.

IDENTIFICATION			TEST CONDITIONS			RESULTS AT STEADY STATE							
Test Group	Heat Sink Configuration	Test I.D.	Inlet Flow Target Temp (-) (°C)	Inlet Flow Rate (-)	Total Input Power (-)	Heat Sink Surface Temperature (-)							
						T_{01}	T_{02}	T_{03}	T_{07}	T_{08}	T_{09}	T_{MAX}	ΔT_{MAX}
1	Benchmark	00/ST	0	1	1	0,31	0,40	0,72	0,74	0,48	0,54	0,74	0,43
2	Stage A	05/ST	0	1	1	0,44	0,35	0,49	0,66	0,61	0,52	0,66	0,31
		06/ST	0	1	1	0,40	0,38	0,50	0,65	0,59	0,50	0,65	0,27
		07/ST	0	1	1	0,46	0,47	0,61	0,66	0,60	0,53	0,66	0,20
		09/ST	0	1	1	0,50	0,48	0,59	0,64	0,60	0,51	0,64	0,16
		10/ST	0	1	1	0,44	0,49	0,55	0,60	0,52	0,49	0,60	0,16
5	Stage 8B	19/ST	0	1	1	0,46	0,41	0,58	0,67	0,59	0,52	0,67	0,26
		21/ST	0	1	1	0,51	0,50	0,62	0,66	0,61	0,53	0,66	0,16
		22/ST	0	1	1	0,45	0,45	0,63	0,68	0,60	0,52	0,68	0,23
		23/ST	0	1	1	0,51	0,52	0,67	0,69	0,62	0,52	0,69	0,18
		26/ST	0	1	1	0,49	0,52	0,65	0,66	0,58	0,52	0,66	0,16
		27/ST	0	1	1	0,45	0,48	0,64	0,67	0,60	0,53	0,67	0,22
		29/ST	0	1	1	0,56	0,55	0,68	0,75	0,67	0,58	0,75	0,20
7	Stage 2B	34/ST	0	1	1	0,63	0,64	0,62	0,67	0,62	0,52	0,67	0,15
		35/ST	0	1	1	0,57	0,46	0,58	0,68	0,65	0,53	0,68	0,22
		36/ST	0	1	1	0,55	0,45	0,55	0,66	0,61	0,51	0,66	0,21
		37/ST	0	1	1	0,47	0,39	0,53	0,66	0,62	0,52	0,66	0,27
		38/ST	0	1	1	0,55	0,47	0,58	0,66	0,67	0,54	0,67	0,20
9	Stage 7B	43/ST	0	1	1	0,56	0,56	0,71	0,64	0,55	0,49	0,71	0,21
		45/ST	0	1	1	0,61	0,57	0,69	0,70	0,66	0,56	0,70	0,14
		46/ST	0	1	1	0,53	0,54	0,61	0,68	0,64	0,56	0,68	0,15

and internal material bonding imperfections. Future research and analysis will drive further consolidation of the new manufacturing processes and insertion methodologies to improve current results.

Some additional experiments have also been carried out to generate a parametric study for the heat sinks behaviour out of the nominal point. The air inlet temperature and airflow impact has been analysed. As seen in Figure 11 for Stage A heat sink, the temperature profiles are almost parallel, showing the expected degradation with higher inlet temperatures and lower mass flows. It can also be observed that for those cases with lower flow rate, the downstream TC's show a relative increase due to the higher outlet airflow temperatures.

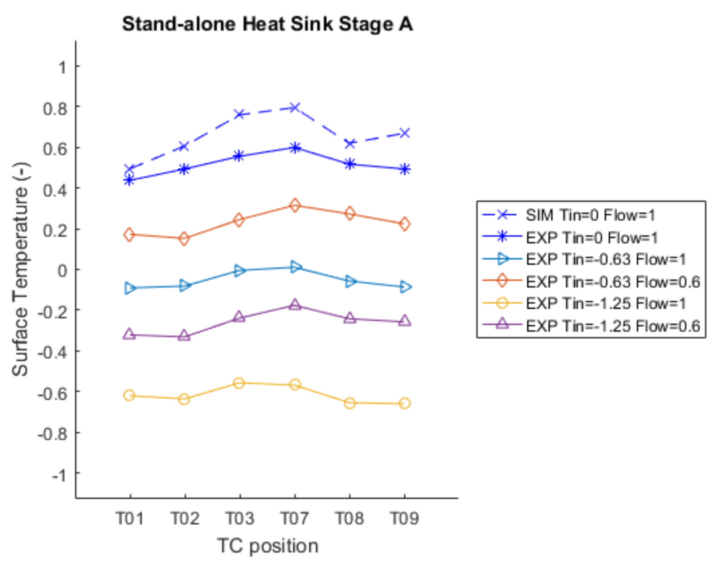

Figure 11: Heat sink parametric study: impact on surface temperatures.

Finally, additional robustness tests (salt-fog, vibration C1 curve) have also been covered with positive results for all four heat sink designs. This is of special relevance for the cases with MMC encapsulant, as it has lower mechanical resistance than aluminium, but shown remarkably enough to comply with the exigent C1 random vibration test.

5. CONCLUSIONS

This paper has briefly shown the work covered in the project ICOPE regarding the design, manufacturing and testing of innovative heat sinks incorporating high-tech carbonaceous materials in their base, specifically APG and ALG MMC's.

The main concept relies in developing a high performance air-cooled heat sink in order to exploit the possibilities that the new wide-bandgap semiconductor materials open to revisit air cooling as the thermal management approach for power electronics. The implementation of the above mentioned high conductivity materials as inserts in the heat sink base have been confirmed as a way to improve significantly the heat sink performance, lowering the maximum base temperature and homogenizing the temperature on all its surface.

The remaining scattering in the temperature measurements, and some results that show less performance than originally predicted by simulation, suggest future research work to consolidate and refine the new combination of manufacturing processes that merge APG and ALG in a single unit.

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ACKNOWLEDGMENT

This paper is related to the work done in the ICOPE project, which has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No. 755556.

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