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Development of Innovative Heat Sinks for Power Electronics Cooling within the More Electrical Aircraft

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Abstract

The thermal management of the power electronics cooling in the aeronautical sector is getting more attention in the recent years due to the progressive implementation of electrical systems in the aircrafts. In the context of new semiconductor materials, the use of highly efficient air cooling is again attracting attention. In this regard, the ICOPE Clean Sky project aims to develop new concepts of air cooled heat sinks that incorporate advanced thermal management materials such as Annealed Pyrolytic Graphite and Metal Matrix Composites, namely Aluminium Graphite. Moreover, the work deals with the integration of the newly developed heat sinks into a thermal management bay. This paper is intended to provide the current project development.

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 [1] framework important research activities, where it is included the presented 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. If feasible, they are expected to reduce the overall weight

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of the cooling solutions compared to liquid or two-phase flow devices, while also adding some benefits in terms of cost, reliability and maintenance.

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 [2] [3] [4]. In this sense, two different high-tech materials were identified by Thales as promising technological bricks, Annealed Pyrolitic Graphite (APG) and Metal Matrix Composites (MMC). Heat sink integration into a power management bay has also been identified as a critical aspect to retain the stand-alone heat sink performances once mounted in the real environment.

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, 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 current stage, and will present the core aspects of the mentioned research in the different tasks, providing the corresponding results and main design conclusions. The first point will be an overview of the project and how it is structured to achieve the desired advanced air-cooled heat sinks.

2. ICOPE project overview

As introduced above, the main goal of this project is the design of innovative and efficient air cooled heat sinks to cool the power electronics modules that are a key component of the more electrical aircraft power management centre design.

The ICOPE Consortium is conceived to tackle the three key points in the development of a solution that covers CleanSky-THALES objectives, by the combination of the expertise in the design of heat sinks with APG (Aavid-Thermal Division of Boyd Corporation), expertise in the field of MMC (Schunk Carbon Technology), and expertise in the analysis of air cooled heat exchangers and air flow in enclosures (CTTC-UPC). On top of this, the long-term experience of CTTC-UPC in the coordination of international projects, particularly Cleansky projects, managing the communication between the Consortium and THALES (as Topic Manager of the project).

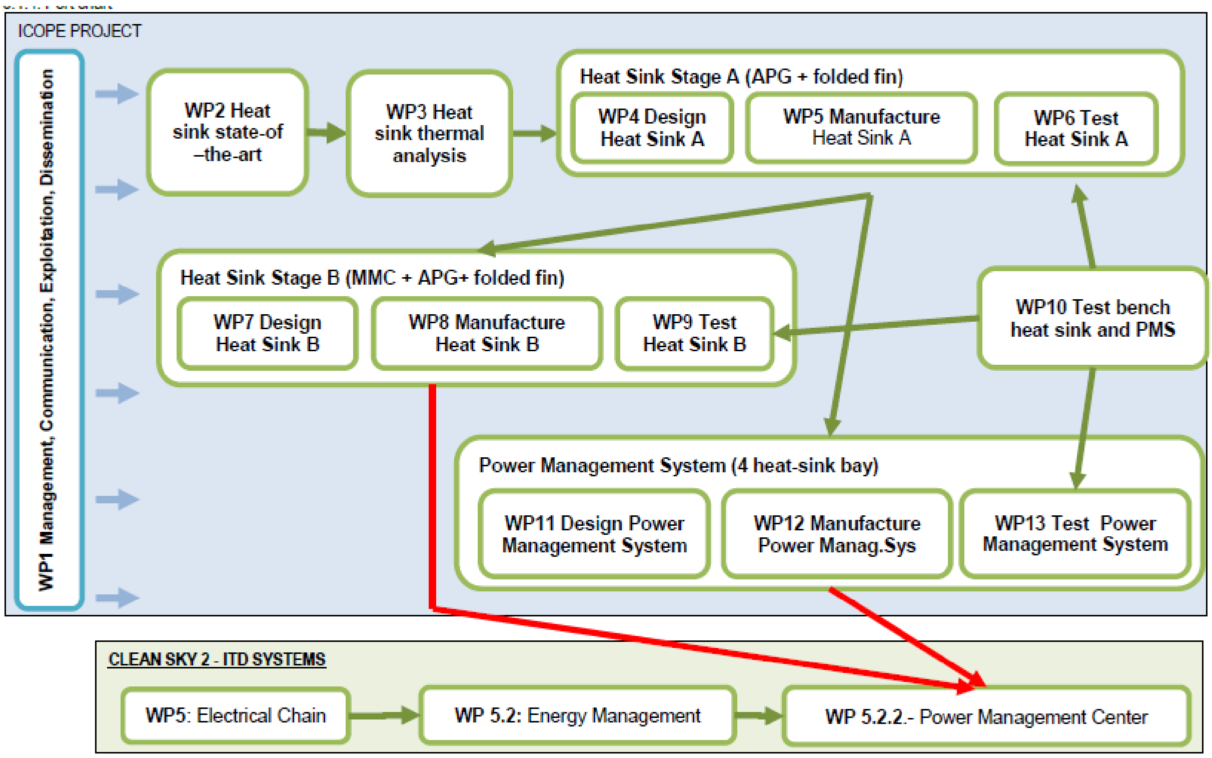

Figure 1: Clean Sky ICOPE Project WorkPlan

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The project has 13 WorkPackages (WPs) as shown in Figure 1. The first WP deals with developing a comprehensive state of the art, in order to provide a better overview of the available technologies and the relative competitiveness of the solutions that can be provided by the current partners. After that, a second workpackage is devoted to a predesign task of both the heat sinks and of the power management bay. This task is crucial to provide a first roadmap to achieve the objectives, while keeping the link between the heat sink and its integration.

The following tasks are divided to the new heat sinks design, manufacturing and testing, all replicated for the two types of heat sink: the first one (A) implements Annealed Pyrolytic Graphite (APG) and folded fins, while the second approach (B) combines Metal Matrix Composites (MMC) with APG.

A final task is devoted to the design, manufacturing and testing of the power management system (bay integrating four heat sinks), to assure a good air distribution among four heat sinks and thus an efficient and reliable cooling.

3. Heat sink design incorporating APG material

3.1 APG description

Aavid-Thermacore is the ICOPE partner that has the capacity to design and manufacture heat sink modules based on Annealed Pyrolytic Graphite (APG). Their commercial brand for this type of product is k-Core, which components are qualified and in production in the UK facility. k-Core material is a composite of graphite and the parent material, significantly improving the thermal spreading. 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). Its thermal conductivity is outstanding in the main planar directions (1700 W/mK), but low in the normal direction (12 W/mK). The APG layer is transversally perforated with some high thermal conductivity vias to overcome the low normal-wise conductivity (Figure 2).

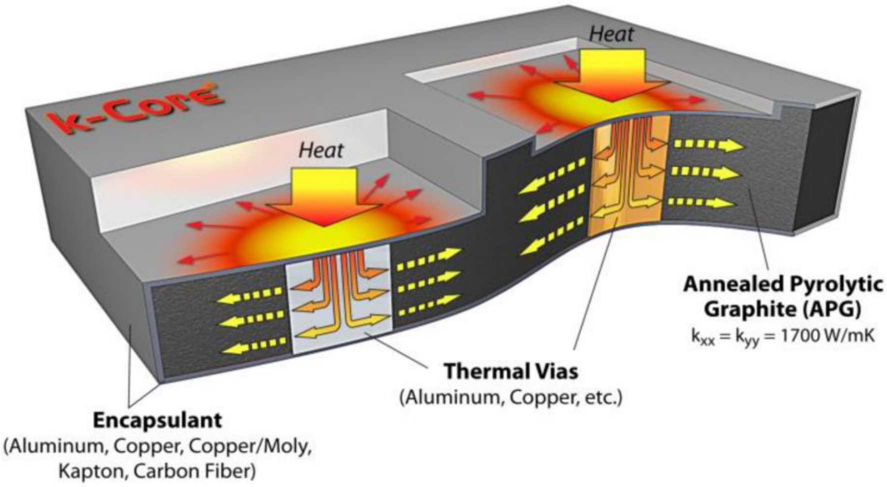

Figure 2: APG integration concept in a heat sink base by Aavid-Thermacore (k-Core product).

K-Core APG provides enhanced thermal features that make it a good candidate for aircrafts application. It has many features and benefits:

- K-Core is lighter than most parent materials and so often provides a direct-weight benefit of 5% compared to Aluminium.
- However due to the enhanced thermal performance compared to standard thermal solutions it allows the designer to use as “Drop-In replacement” for equivalent solid conduction and allows to reduce the size and weight of electronics packages or increase the performance.
- It is a passive thermal solution and the thermal spreading is not affected by gravitational forces.
- Significantly reduced peak semi-conductor temperatures. There is a relative improvement in thermal conductivity.
- It has a wide operational temperature from -123ºC (150K) to 125ºC (398K) .
- 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
- Available configurations are fully flexible to the needs of the customer.

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In order to visualize better the benefits of the k-Core in terms of thermal conductivity (which is one of the key aspects at the project), Figure 3 and Figure 4 show on one hand the significant improvement in thermal conductivity with the application of different encapsulant materials. We can also compare the thermal conductivity in different directions between APG and typical parent materials.

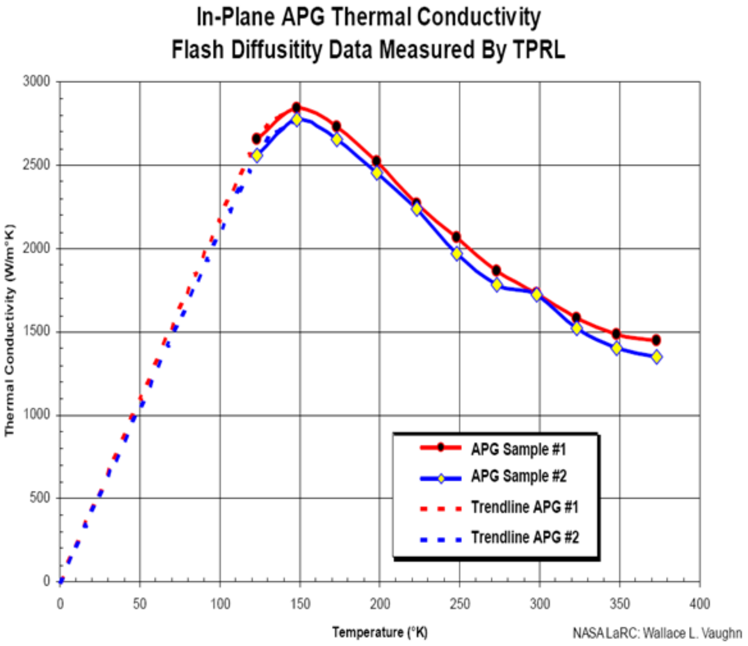
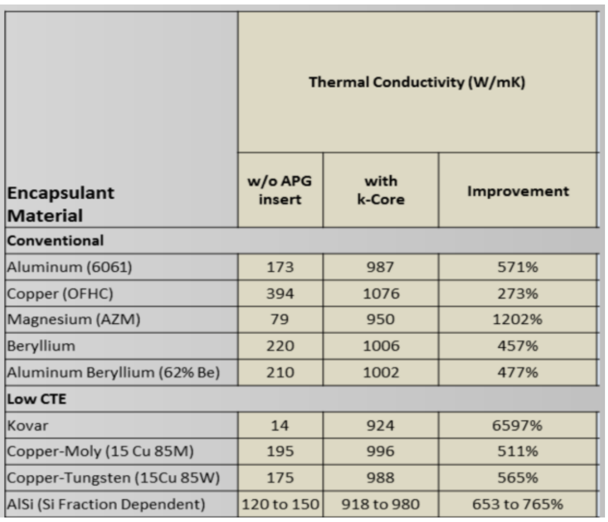


Figure 3: In-Plane k-Core APG thermal conductivity.



Encapsulant Material	Thermal Conductivity (W/mK)		
	w/o APG insert	with k-Core	Improvement
Conventional			
Aluminum (6061)	173	987	571%
Copper (OFHC)	394	1076	273%
Magnesium (AZM)	79	950	1202%
Beryllium	220	1006	457%
Aluminum Beryllium (62% Be)	210	1002	477%
Low CTE			
Kovar	14	924	6597%
Copper-Moly (15 Cu 85M)	195	996	511%
Copper-Tungsten (15Cu 85W)	175	988	565%
AlSi (Si Fraction Dependent)	120 to 150	918 to 980	653 to 765%

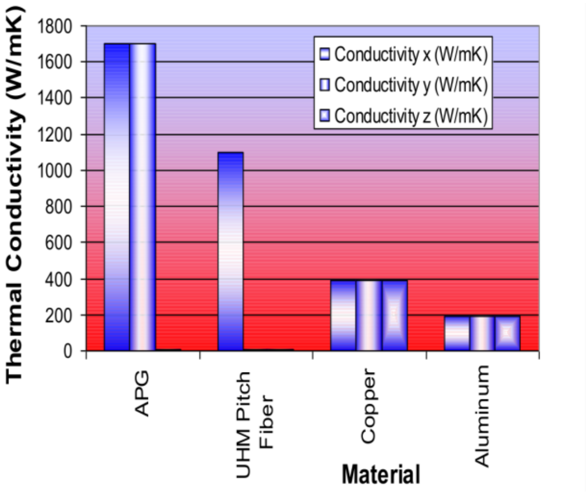


Figure 4: k-Core thermal conductivity features.

3.2 Heat sink A analysis and design

The work on the heat sink predesign has combined the engineering and thermal analysis capabilities of the partners by using two main analysis techniques. The predesign heat sink geometry has evolved by combining specific simulations with industrial oriented CFD models for a set of concepts-geometries. On the other hand a more extensive simulation and optimization using simplified models 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 designs (left), and specific geometry values for each individual within the Pareto front (right).

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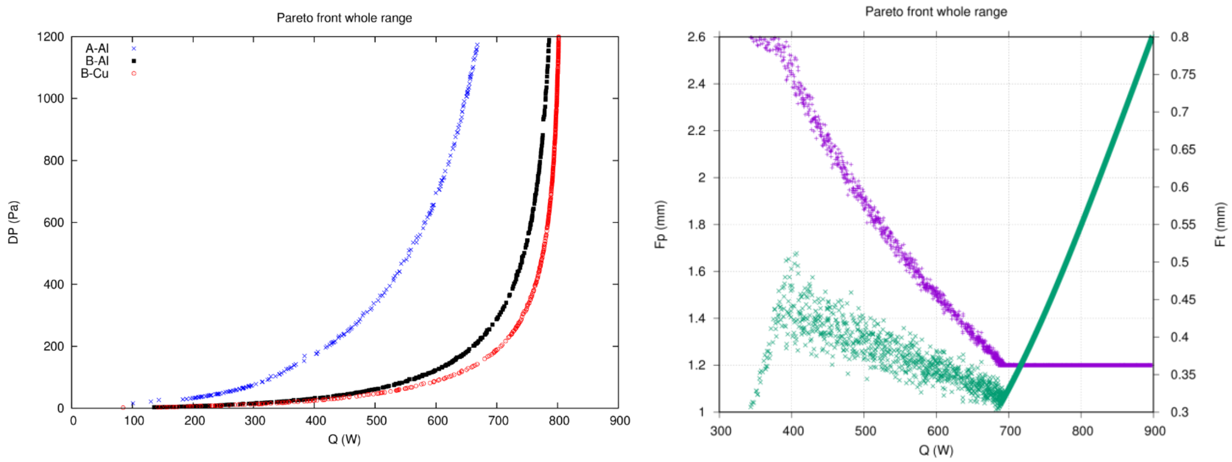
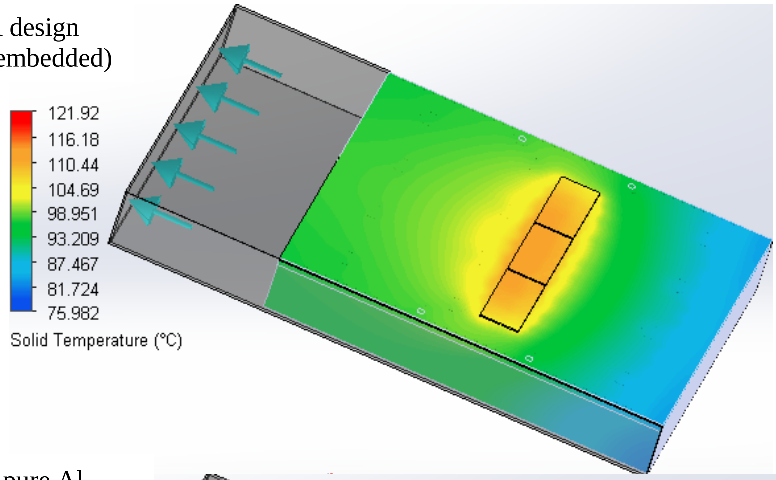


Figure 5: First numerical analysis of the heat sink using the eNTU-GA numerical tool.

Both tools provided at the end similar suggested designs, that have acted as the initial seed for further design during WP4, which has been fundamentally based on industrial oriented CFD models. Within this WP, the solution has started without considering insertions of APG, for thereafter improving the initial design integrating the high thermal conductivity material. In Figure 6 CFD simulation results are given as illustrative of the developed design process, comparing the performance with and without insertions.

a) Heat sink A design step (APG embedded)



b) Heat sink pure Al design step

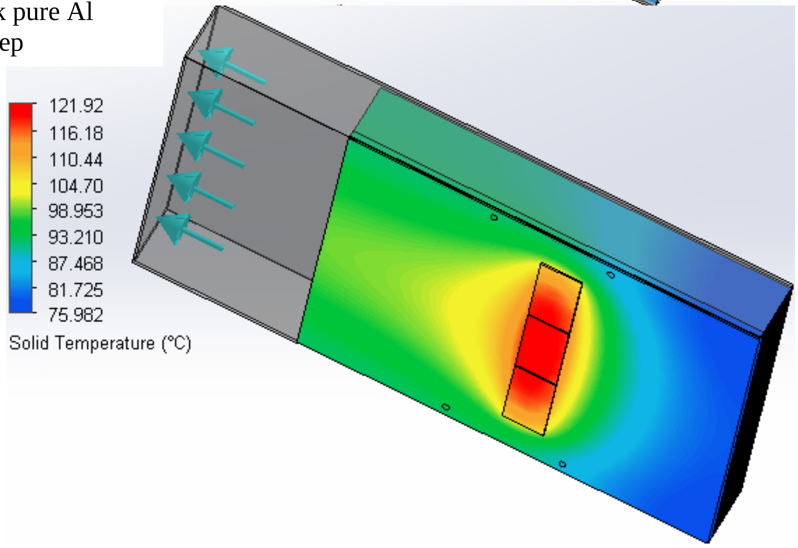


Figure 6: CFD analysis of heat sink A design step. Top: unit with APG insertions. Bottom: pure Al solution.

The design process finished with the identification of a suitable solution from the simulation results, meeting all of the project requirements (weight 1.41 kg (< 1.5 kg), T_{max}=109.84ºC (<110ºC), ΔP=260 Pa (<500 Pa)).

After this decision, the Consortium started the process to translate this design into a manufacturable unit. The main aspect 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 (Figure 7), which construction encloses the fins so that no additional containment of the air is required and there is minimal air leakage. The fin stack is then bonded to the heat sink base to provide adequate thermal connection. A simplified diagram of the heat sink, for confidentiality constraints, is given in Figure 8.

The heat sinks for this stage A are currently finishing the manufacturing process. The heat sink bases integrating APG have already been manufactured, machined and the plating process is finishing. Fin stacks are already available.

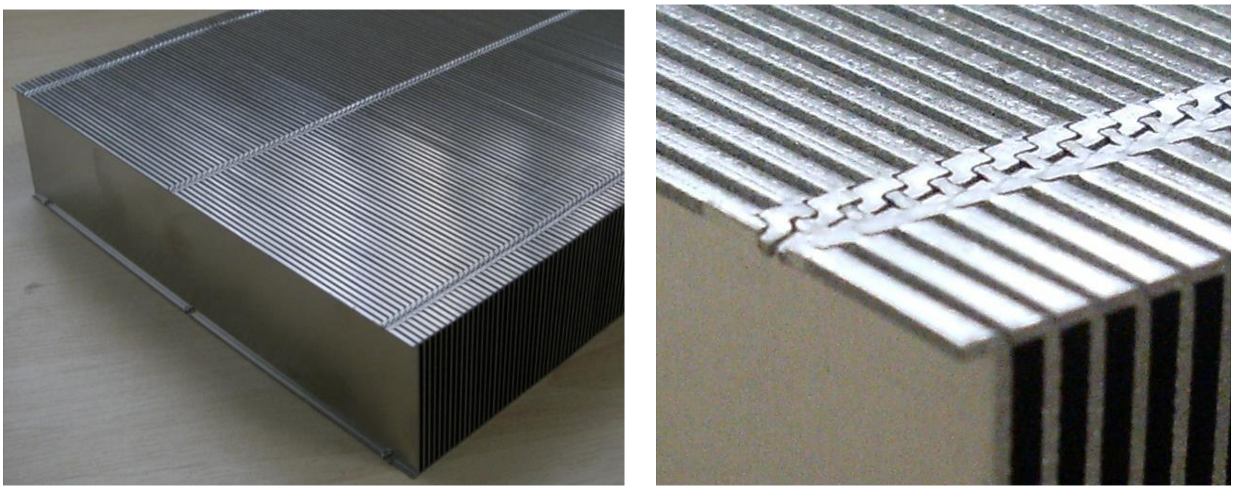


Figure 7: Detail of the fin stack and the connections points between fins.

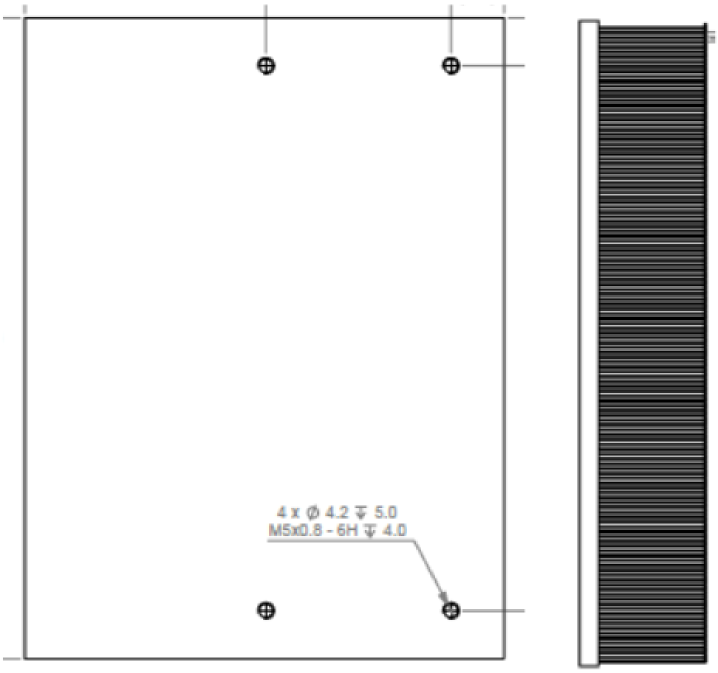


Figure 8: Simplified diagram of the heat sink final design.

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4. Heat sink design incorporating MMC material

4.1 MMC description

Schunk Carbon Technology is providing the Metal Matrix Composites (MMC) within the ICOPE consortium. Schunk's Aluminium Graphite (ALG) products 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 9 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.

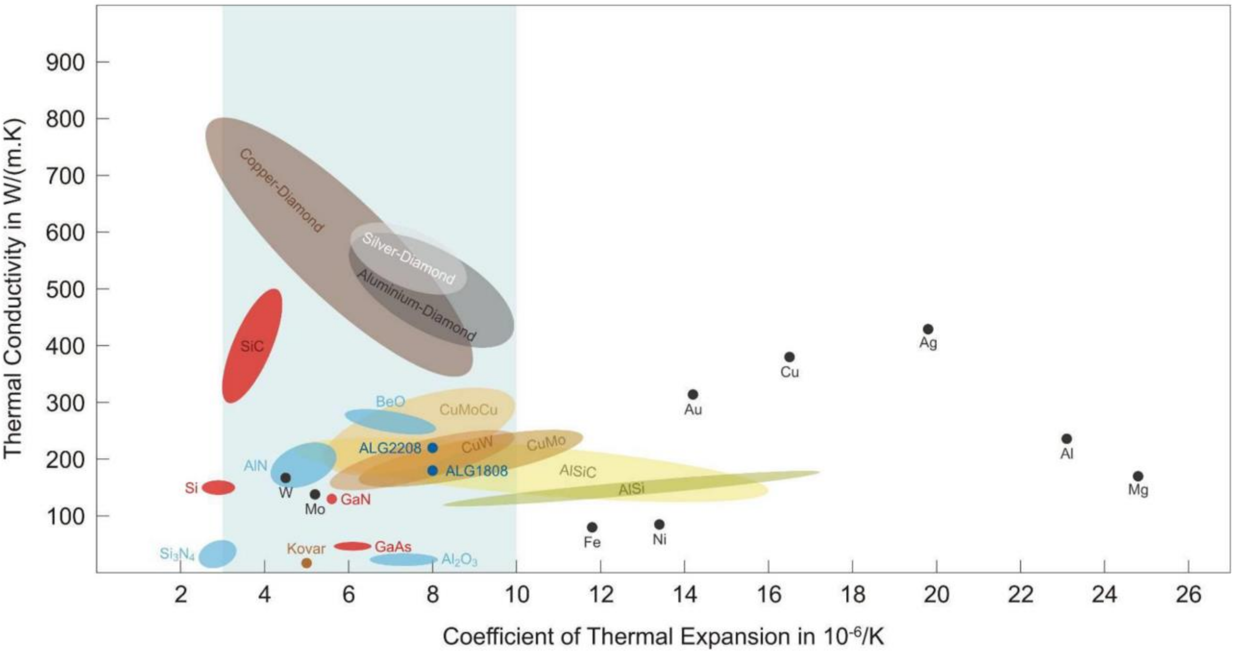

Figure 9: Coefficient of thermal expansion of ALG and comparison to other materials.

Despite the strong change in internal microstructure generated by the presence of the graphite matrix, ALG maintains a very high thermal conductivity, equivalent to that of aluminium, making it a high thermal conductivity material ideally suited for applications in air-cooled heat sinks, where the dominant thermal resistance remains on the airside (no need of higher conductivity materials with higher cost or higher weight). 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.

Schunk's ALG MMC is based on synthetic graphites. These graphites are then infiltrated with liquid aluminium. Once solidified, the two interlocking matrices form the composite material ALG (Figure 10).

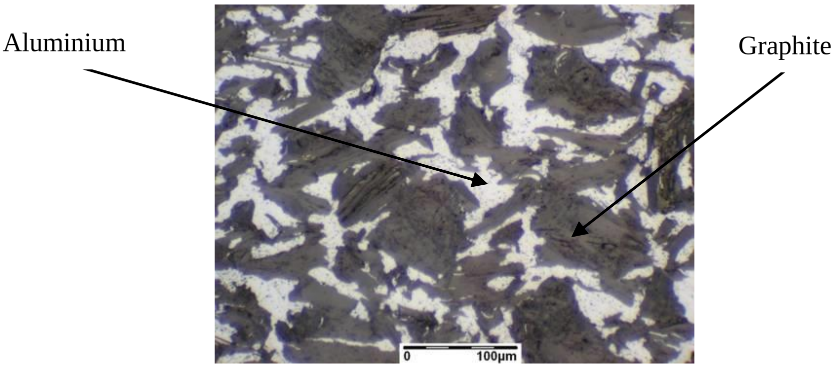

Figure 10: The microstructure of ALG showing the two interlocking matrices

The individual parts required for each specific application are machined from the solid blocks. Compared to other commercially available MMCs (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 11). 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.

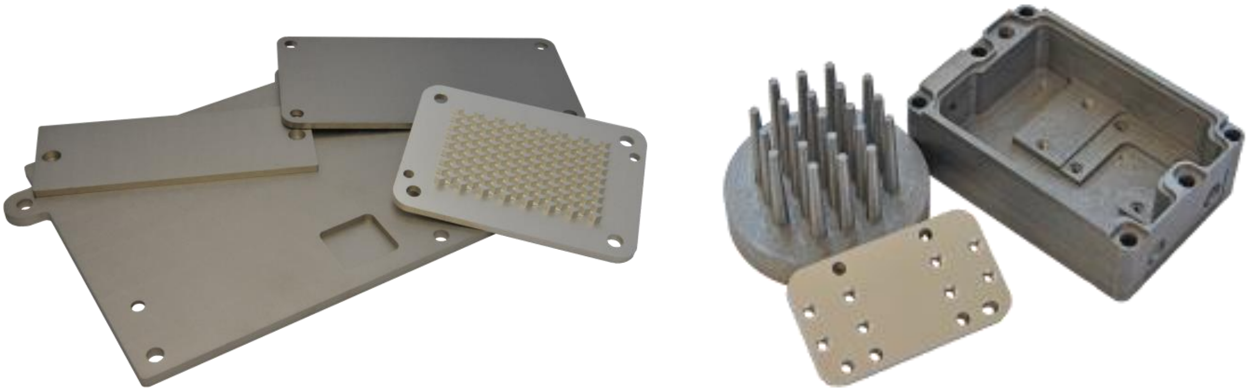

Figure 11: Base plates and coolers for power modules (left), heat sinks and housings for laser diodes (right).

4.2 Heat sink B analysis and design

After closing the design of the Stage A heat sink, the project efforts have been focused in the development of a second innovative heat sink incorporating MMC materials on top of the APG base. The consortium has pursued to keep the internal structure of the Stage A heat sink, but suggesting new combinations of materials for the internal base insertions and for the heat sink base encapsulant.

At the end of the day three different solutions have been identified by CFD numerical simulation as promising, one is keeping Al as encapsulant and the two others are introducing MMC as encapsulant. The benefits introduced by the different options are presented in Table 1 on a relative basis comparing to Stage A results.

The Consortium is currently starting the manufacturing of the heat sink bases and the corresponding insertions. After that, the heat sinks will be assembled (bases with fin stack), and tested (first stand-alone and then integrated in the duct assembly).

For those new combinations of materials, the Consortium has manufactured coupon samples, in order to verify the manufacturing process, the quality of the bondings, and also to quantify the final effective conductivity of the innovative composites. Schunk has developed a particularly designed experimental unit (Figure 12) to characterize the thermal conductivity of these new materials, as conventional measuring techniques were failing due to the extremely thin layers involved in this case.

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Table 1: Solutions identified for Stage B design incorporating MMC products

Heat Sink	Base material	Inserts	Tmax dif (vs. A)	Weight ratio to A
A	Al	APG	0	1
2b	MMC	APG	+1.15	0.964
7b	MMC	APG+MMC-anisotropic	-1.24	0.963
8b	Al	APG+MMCanisotropic	-1.03	0.980

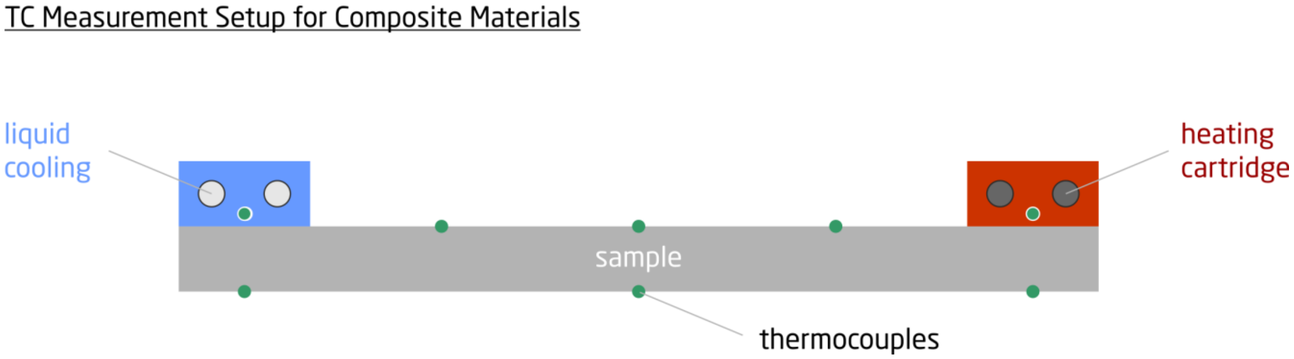

Figure 12: Diagram of the thermal conductivity characterization experimental unit at Schunk Carbon.

5. Bay integrating four heat sinks

5.1 Design

The Consortium, starting from the indicated requirements and restrictions indicated by THALES, has proceeded to the identification of the best design and layout of the power management bay, in terms of required space and components distribution. A preliminary design of the bay can be seen in Figure 13.

The design also affects two additional lower levels. On one side the duct assembly (preliminary design is presented in Figure 14), that is, the air flow layout and ducting which provides a well-balanced air flow between the four integrated heat sinks. Here the main target is to obtain not only adequate total air flow per unit, but also a uniform velocity distribution at each inlet. A compromise has to be found to achieve these objectives up to a certain level, while minimizing the required space.

In addition to the duct assembly, we have a second nested level, related to the necessity to integrate the heat sinks in a replaceable way. This implies the design of the so called Power Electronic Module (PEM), a box containing some electronic components plus the heat sink that can be extracted and replaced from the duct assembly in a flexible way (preliminary design example shown in Figure 15).

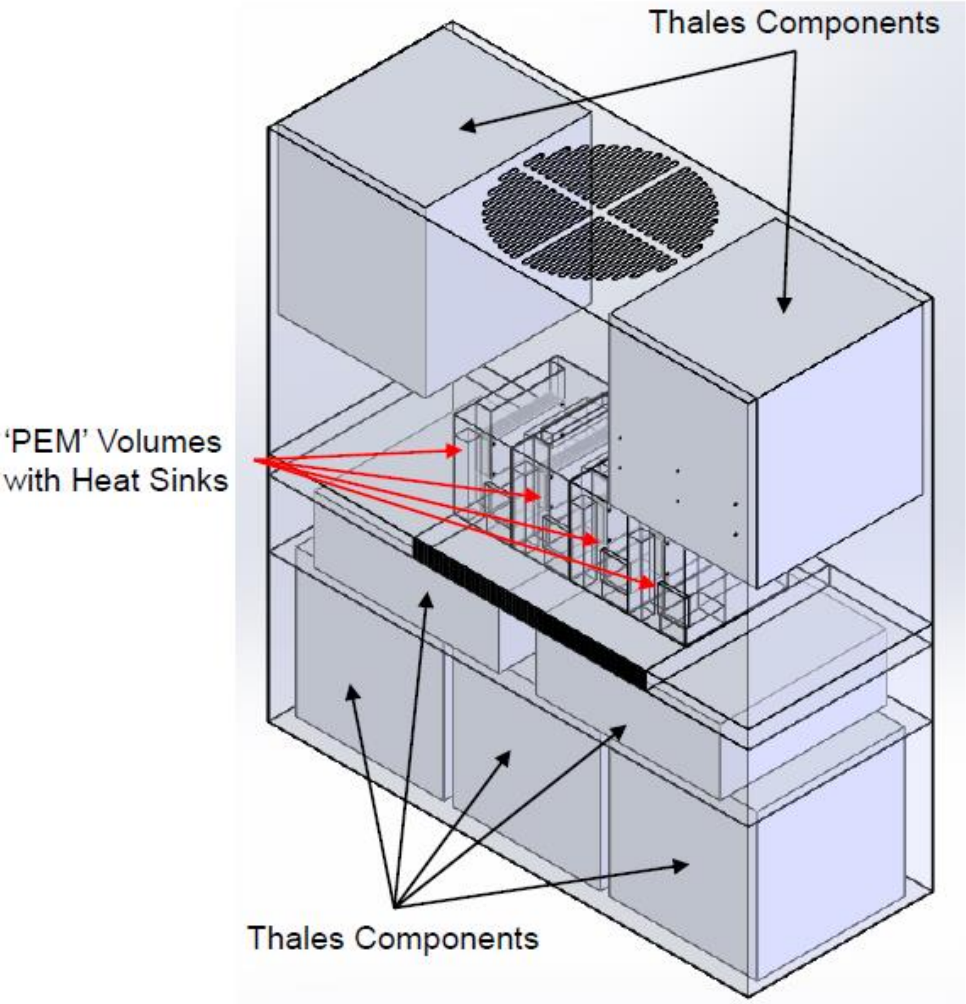

Figure 13: CAD model of the preliminary bay design, incorporating the Thales components and the PEM modules with adequate flow alignment.

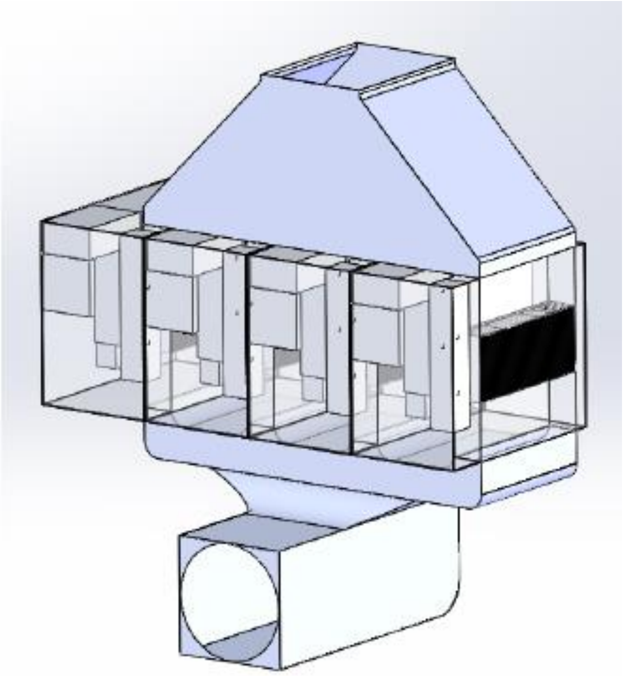

Figure 14: Ducting assembly that distributes the air flow among four PEMs. Preliminary design.

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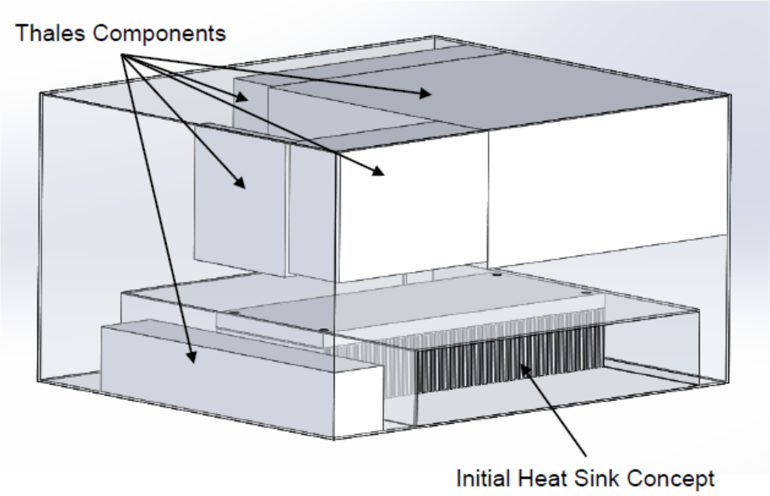

Figure 15: Power Electronic Module preliminary configuration.

5.2 CFD analysis

CTTC-UPC has carried out a systematic CFD study of the duct assembly geometry and layout, changing the unit shape, orientation, and internal configuration. The commercial CFD package Fluent [5] has been used for the analysis. Reynolds-Averaged Navier-Stokes equations (RANS) are used to solve the turbulent flow using the k-ε Realizable turbulence model [6]. The heat sink volumes have been simplified as porous media blocks with equivalent flow resistance in order to avoid solving the flow in the smaller dimension of heat sink channels. One of the preliminary cases analysed is shown in the following figures to illustrate the work carried out. For this particular case, the flow distribution obtains a good balance between heat sinks, specifically for the two interior passages 3% higher than the average flow, and for the two exterior passages 3 % lower. In the final design this was even reduced.
As observed in Figure 16, flow separation does not occur at the entrance to the passages thanks to the rounding of the corners. However, it is observed after the main turn at the inlet (Figure 17). In the same figures we can identify that even though the flow distribution is correct, we have velocity non-uniformity at the inlet of the heat sink. This aspect has been minimized in the final design. Regarding the temperature distribution, no relevant differences are observed between the four heat sinks, only those due to the slight deviations in individual air flows (Figure 18).

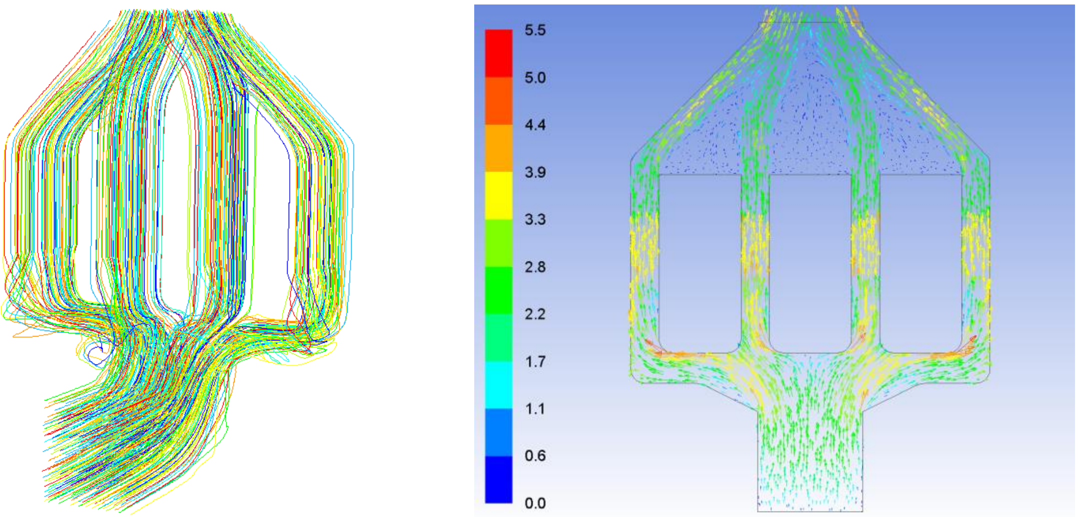

Figure 16: Illustrative case velocity distribution. On the left, streamlines. On the right, velocity vectors.

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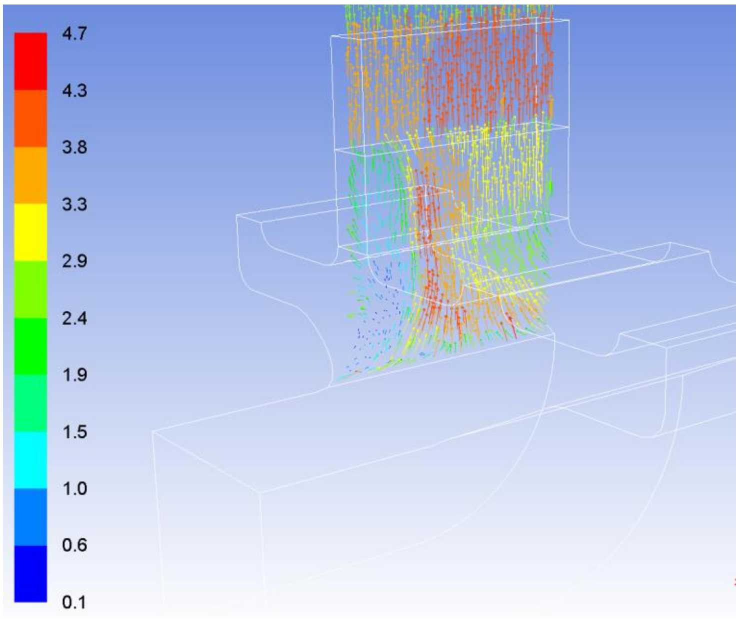

Figure 17: Illustrative case velocity vectors after the inlet turn.

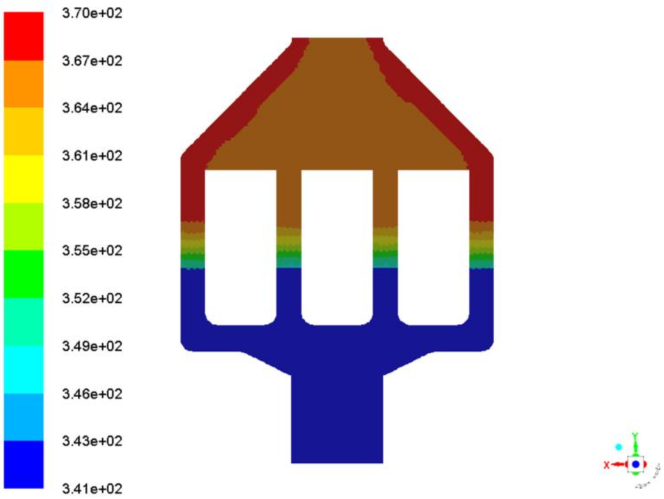

Figure 18: Illustrative case temperature distribution.

6. Experimental set-up for heat sink and duct assembly testing.

Aavid has the test equipment capabilities to produce the specified environmental conditions outlined for the project. The Aavid air flow chamber has a capacity to deliver a fully developed flow up to 250g/s. Delivery temperature up to 70˚C are controlled using adjustable heat guns at the fan inlet and monitored by thermocouples positioned at the product under test inlet.

The Aavid airflow chamber was manufactured by Airflow Management Systems (Figure 19). Airflow is set using differential pressure measurements across a venturi within the chamber. Flow then passes through a series of baffles, which creates an evenly distributed flow to the chamber outlet. The outlet allows for the fixation of bespoke discharge spigots for various test applications (Figure 20). 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.

The chamber operation manual provides nozzle configurations for various flow ranges. Flow ranges are set by manually opening/sealing these nozzles. 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.

Figure 21 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 wetted perimeter of this spigot will match that of a PEM ventilation channel. The heat sink fin stack will slot into this spigot at a distance where flow is considered fully developed. Also shown in the same

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figure is a bespoke frame designed to support the spigot and heat sink. The design of this frame is adjustable and can therefore be utilized for the subsequent power management system test bench. The same unit with some adaptations will be used for thermal testing of the duct assembly with four heat sinks.

Figure 19: Air Flow Chamber

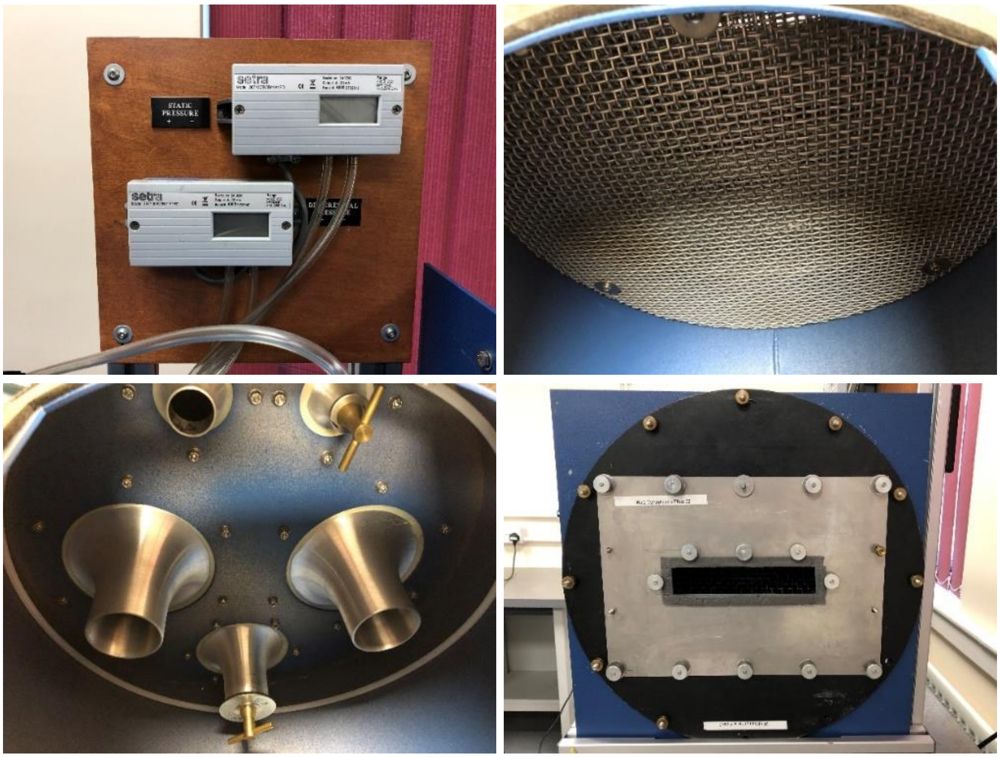

Figure 20: (Clockwise) Pressure displays, baffle mesh, outlet fixing and flow nozzles.

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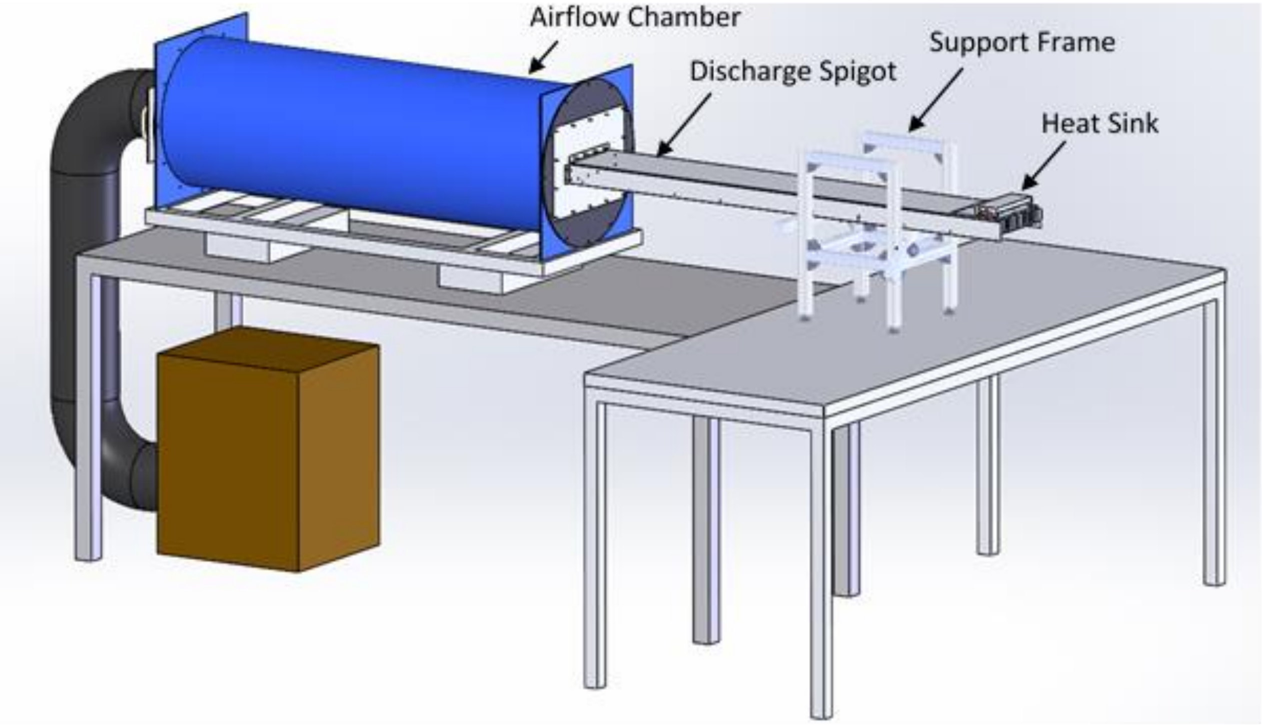

Figure 21: Heat Sink Test Bench Concept

Figure 22 is an exploded view of the heater block fixation method to the heat sink. To guarantee accurate heater block positioning, an aluminium jig will locate 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.

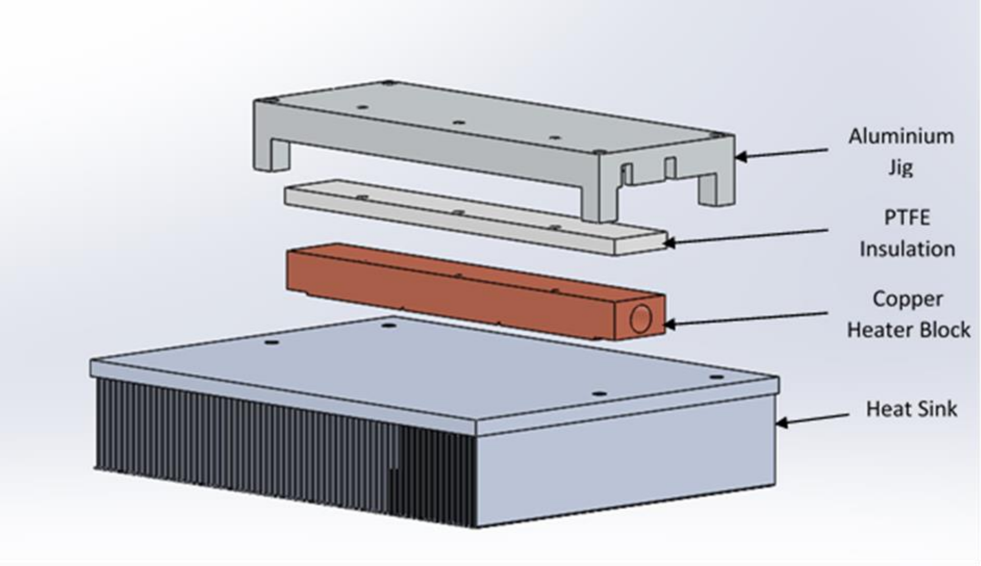

Figure 22: Heater Block Assembly

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6. Conclusions

This paper aims to present the ICOPE project, in its structure and objectives, but specially to show to the public audience the evolution of its activities. A brief introduction of the two main innovative materials involved in the design of the innovative heat sinks are presented, as considered of interest for a general reader, and also to allow a better understanding of how these materials can fulfil the project objectives.

Summarising the objectives achieved till now, first the Consortium has designed a suitable solution for heat sink incorporating only APG (Stage A), which is now in advanced manufacturing stage.

In the same way, the partners have identified three different alternative combinations of materials that lead to the corresponding heat sink designs for Stage B. This stage is now finishing the design process and starting the manufacturing steps.

Finally, regarding the integration into a power management bay, the consortium has already designed by simulation a suitable solution that covers simultaneously an adequate mass flow balance between the four heat sinks, and correct velocity uniformity at the inlet of each heat sink. This has been achieved with a very compact solution, reducing initial requirements of bay size.

The project is now entering in its final phase, closing the manufacturing and starting the testing phase, while keeping simulation activities to provide further information on top of the experimental data.

Acknowledgements

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