Proceedings of the 11th World Congress on Mechanical, Chemical, and Material Engineering (MCM'25)
Paris, France - August, 2025
Paper No. HTFF 195
DOI: 10.11159/htff25.195

Insights on the Ongoing Project VISIONS: Evolutionary Design of Innovative Heat Transfer Devices

Assunta Andreozzi[1], Nicola Bianco[1], Rosa Francesca De Masi[2], Andrea Fragnito[1], Marcello Iasiello[1], Fabio Iozzino[2], Gerardo Maria Mauro[2], Vittorio Orlanducci[2]
[1]Università degli Studi di Napoli Federico II, Department of Industrial Engineering
Piazzale Tecchio 80, 80125 Napoli, Italy
assunta.andreozzi@unina.it; nicola.bianco@unina.it; andrea.fragnito@unina.it; marcello.iasiello@unina.it
[2]Università degli Studi del Sannio, Department of Engineering
Piazza Roma 21, 82100 Benevento, Italy
rfdemasi@unisannio.it; fiozzino@unisannio.it; vorlanducci@unisannio.it
[3]Università degli Studi di Napoli Federico II, Department of Architecture
Via Forno Vecchio 36, 80134, Napoli, Italy
gerardomaria.mauro@unina.it

Abstract - VISIONS (eVolutIonary deSign for Innovative heat traNsfer deviceS) is a research project focused on developing high-performance thermal systems by integrating topology optimization (TO) and computational fluid dynamics (CFD), based on the principles of evolutionary design as described by the constructal law. This approach enables the creation of free-form, highly efficient thermal architectures inspired by nature, while ensuring manufacturability via additive manufacturing (AM). The project targets two key applications: advanced electronic cooling and latent thermal energy storage. For electronic cooling, the goal is to prevent local overheating and ensure temperature uniformity, which is essential for the reliability and longevity of electronic devices. For thermal energy storage, the focus is on improving the energy density and responsiveness of phase change materials (PCMs) that can be integrated with intermittent renewable energy sources to improve system dispatchability. The methodology begins with CFD-based thermal characterization of PCMs, followed by the application of TO strategies to optimize geometries, often mathematically parameterized. These designs are evaluated for thermal conductance, stability, and integration of advanced materials. By combining PCMs with the TO+CFD framework, significant improvements in both performance and sustainability are achieved. The final phase will involve AM-based prototyping of two devices: a PCM-enhanced heat sink for electronics and a latent heat thermal energy storage. VISIONS aims to promote sustainable energy use by advancing energy-efficient thermal management in electronics and optimizing thermal storage in renewable energy systems, contributing to the broader goals of energy transition and climate neutrality. The project is still ongoing and continues to research and develop to achieve the goals set.

***Keywords*:** Heat transfer device; thermal management; thermal storage; topology optimization; phase change materials, additive manufacturing

1. Introduction

Over time, the objectives for prototyping heat transfer devices have evolved, shifting from smooth operation, reliability, and low costs to a broader focus on sustainability. This shift is a crucial consideration in the design of engineering systems. In the context of applied thermodynamics, this transition translates into the need to address various factors, including high compactness [1], high energy density [2], stable operating temperatures, and economic feasibility [3]. For example, one of the current challenges in research is the development of compact and economically viable devices capable of dissipating high heat fluxes, up to 1000 W/cm² [4], in order to prevent dangerous temperature rises. Conversely, thermal storage systems are focused on storing significant amounts of heat with minimal temperature variations while also achieving rapid charging and discharging processes [5]. The primary goal is to control the heat transfer mechanism, considering that each factor involved in heat transfer – such as fluid type, geometry, and operating conditions – can serve as a design variable. On one hand, air-free and forced convection systems – widely used in information technology (IT) equipment – are characterized by

poor heat removal rates. On the other hand, they offer simplicity and reliability [6]. In this context, phase change materials (PCMs) have emerged as high-performance solutions, effectively addressing the need for temperature control and high energy density [7]. However, depending on the type, PCMs can face challenges such as low thermal conductivity, thermal instability, and cycling issues, etc [8]. To address fluid-related challenges, thermal devices incorporating PCMs can be enhanced through various techniques, such as the use of fins, metal foams, and nanoparticles. In the thermal management of electronic devices, PCMs integrated with heat sinks featuring internal pin fins are frequently utilized [9]. Porous media with gradient characteristics that influence both thermal and hydraulic performance [10], as well as customized foam morphologies designed to maximize heat transfer efficiency [11], have been demonstrated as effective solutions. Additionally, architected structures or triply periodic minimal surfaces, which can be fabricated using 3D printing, have shown promising results. To enhance the competitiveness of these technologies and expand their real-world applicability, significant efforts have been directed toward the use of topology optimization (TO) [12]. TO represents the pinnacle of evolutionary design, enabling the identification of complex, optimal structures [13] and enables the strategic placement of highly conductive materials where they are most needed [14], simplifying the design by reducing material usage and rearranging its structure to achieve the desired performance objectives [15]. In this context, the growth of additive manufacturing (AM) - well suited for creating effective representations of freeform designs - aligns perfectly with the goals of TO research. Despite promising developments, few studies have actually fabricated and tested TO structures.

There is still significant room for improvement in the integration of TO-derived heat transfer devices and with AM solutions, an area that is the focus of the VISIONS research proposal. The state-of-the-art highlights a persistent need for optimized design strategies for heat sinks and heat exchangers, with particular reference to thermal management and energy storage systems. In this context, the project aims to address this gap by designing and prototyping advanced solutions that enhance the synergistic potential offered by the integration of TO and AM.

2. Materials and methods

This section outlines the steps undertaken in the VISIONS project, starting with the characterization of methods and tools for computational fluid dynamics (CFD) and topology optimization (TO), and evaluating potential coupling strategies. The final step involves using the integrated CFD and TO approach to design the optimal solutions for a heat exchanger using a heat sink incorporating phase change materials (PCMs).

2.1 Framework of the VISIONS project

The eVolutIonary deSign for Innovative heat traNsfer deviceS (VISIONS) is a 24-month ongoing research project focused on the development of advanced and sustainable heat transfer devices through an evolutionary design approach that integrates topology optimization (TO), computational fluid dynamics (CFD), and additive manufacturing (AM). The project is structured into four main work packages (WPs), each of which plays a significant role in the development of advanced and sustainable heat transfer devices, as shown in Figure 1, as hereby described:

- WP1 – Application of evolutionary design via TO to heat transfer devices, with focus on heat sinks/exchangers.
- WP2 – Integration of TO-based solutions for the design of heat sinks whit phase change materials (PCMs).
- WP3 – Integration of TO-based solutions for the design of heat exchangers with hybrid nanofluids.
- WP4 – Prototyping and Testing involves the fabrication and experimental validation of the optimized devices using 3D printing for prototyping. These devices will be tested in lab to verify their thermal effectiveness and performance, thus completing the project's development cycle.

Each work package builds on the previous one, taking the project from the conceptual phase to the creation of real prototypes, with the ultimate goal of developing efficient, scalable, and sustainable thermal technologies.

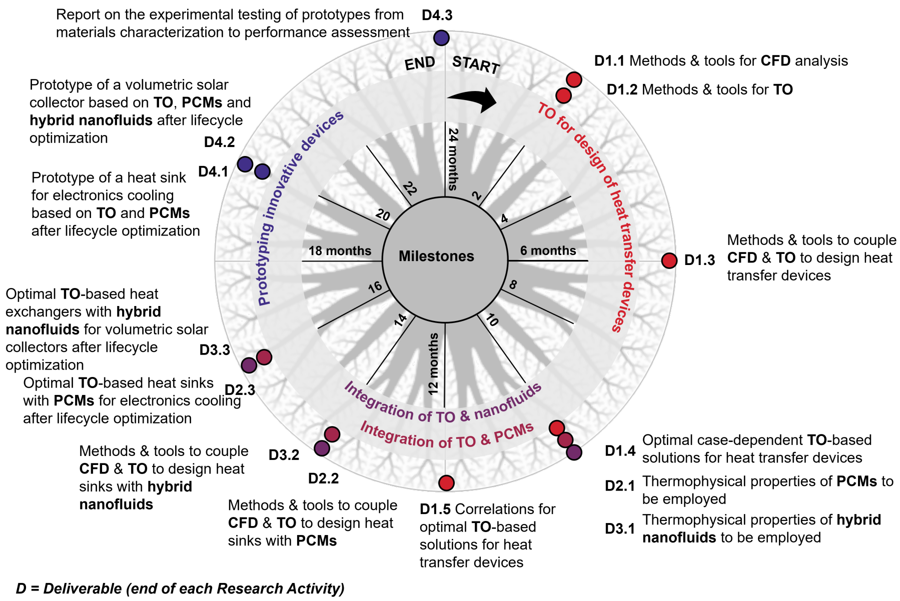


Fig. 1: Project Timeline: Deliverables.

2.2 Methods and tools couple CFD and TO

To effectively achieve the objectives of the project, several case studies focusing on heat transfer problems were selected. Specifically, the thermal management of PCMs has been studied in conjunction with CFD analysis, performed using finite element solvers (FEMs) such as COMSOL Multiphysics, which provide significant advantages in solving the differential equations governing the physical phenomena involved. The use of PCMs has been explored for both thermal energy storage and electronic applications due to their ability to absorb and release energy during phase transitions. A thorough understanding of the melting process is critical to improving the performance of these systems and optimizing the use latent heat. Case studies have focused on thermal management using PCMs, optimization of innovative heat sinks, and efficiency of volumetric solar collectors. In the first studies, CFD analysis evaluated the effect of different periodic structures, such as cubic and octahedral geometries, on the melting rate of PCMs in an isolated cubic domain. The parameters included the melting time, temperature distribution and stored energy. The results indicate that the geometry significantly affects the melting process by increasing the exchange surface area and, consequently, the enhanced equivalent thermal conductivity. Due to the high computational cost of FEM simulations, a simplified predictive model was initially developed based on a fixed grid approach and an equivalent heat capacity. The model also incorporates effective thermal conductivity to simulate natural convection through a tuned Nusselt-Rayleigh correlation. When validated against finite element CFD solutions, the model demonstrated good agreement in predicting the liquid fraction and temperature evolution, providing an efficient alternative for the study of PCMs [16]. A crucial aspect of the project was the development of topological optimization (TO) techniques and related codes to optimize heat transfer devices. TO allows the determination of the optimal material distribution in a domain in order to minimize functions such as thermal resistance or mean temperature. Using numerical methods such as FEM and a pseudo-density variable, the distribution is iteratively optimized. As an initial case, the point-volume model was analysed and used as a reference to test TO algorithms applied to heat sinks. The study shows how variations in the SIMP (Solid Isotropic Material with Penalization) interpolation parameters, such as mesh size (**Es**) and penalty factor (**p**), influence the optimal solutions. All configurations considered maintained the same volume fraction (**Vf**), representing the percentage of solid material within the total volume. The obtained configurations show structures similar to natural branching, validated under stationary conduction conditions. The optimal solutions obtained for steady-state heat conduction validated this analogy. The results from varying mesh size (**Es**) and penalty factor (**p**) were compared with those from the reference study [17], as shown in Figure 2, and exhibited excellent agreement.

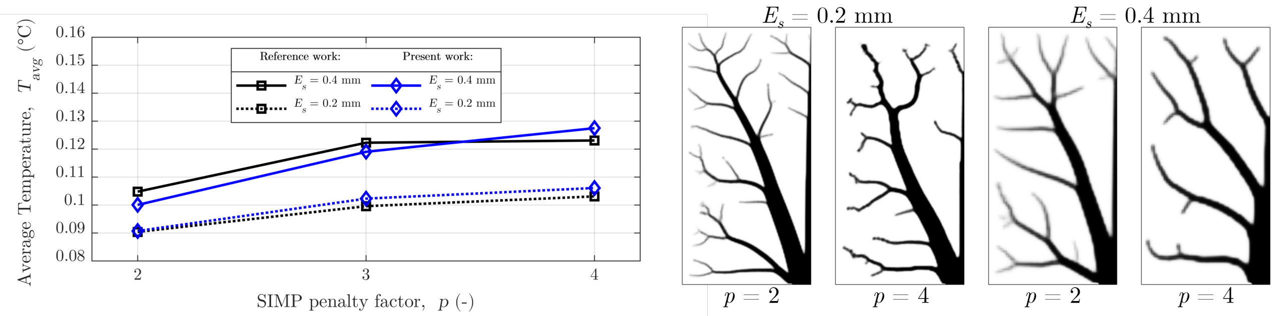


Fig. 2: Verification and visualization of topology optimization results.

2.3 Different approaches to implement TO

The goal is to integrate TO with the complex CFD analysis of PCM thermal behaviour. Phase change materials are highly effective for thermal energy storage and temperature. However, their low thermal conductivity is a limitation, which can be overcome through the use of TO. To combine these tools, recent advancements in traditional topology optimization techniques, such as multi-material topology optimization (MMTO), are essential. MMTO allows for the inclusion of a broader range of materials, thus increasing the system's flexibility and improving its thermal performance. Both TO and MMTO have been applied to benchmark problems in thermal conduction, such as cooling circular or square 2D sections with uniform heat generation. In these cases, the outer edge is insulated, while the inner edge, at constant temperature, serves as a heat sink, an ideal configuration for studying heat sinks. Notably, traditional TO allows selection between high conductivity materials and voids, while MMTO allows more complex distributions. The SIMP algorithm, which penalizes physically insignificant solutions, is employed to determine the optimal material distribution, with differentiation between materials achieved by adjusting the interpolation and projection parameters. In the cases examined, the primary objectives of the analysis were either to minimize total thermal resistance or to reduce the average temperature of the system. The results show that MMTO provides superior performance compared with traditional TO and complex branched structures. Specifically, the optimal solution varies depending on the objective: when minimizing thermal resistance, the optimal geometry has two central and two lateral branches to maximize domain coverage. In contrast, when minimizing the average temperature, five main branches are created, which are thinner and more evenly distributed. Figure 3 shows three optimization approaches: traditional TO, a repeated branched structure, and MMTO primarily using solid and porous materials, with varying arrangements for minimizing thermal resistance. This methodology can be applied to various cases, including PCMs offering new opportunities for advanced thermal management.

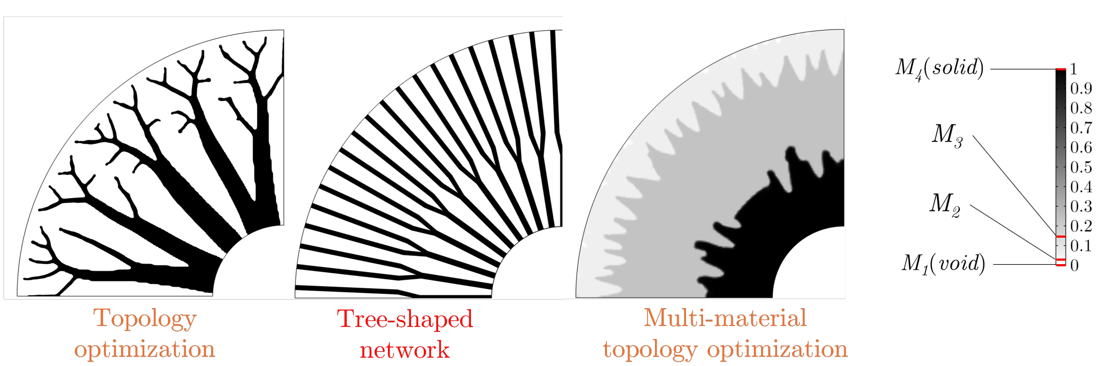


Fig. 3: Tree-shaped, TO and MMTO solutions for minimizing thermal resistance.

2.4 A new approach to reproducing TO

An intriguing approach to topology optimization involves correlating TO-designs with fractal-based structures, enabling the derivation of simple relationships to create sub-optimal configurations that mimic the potential of TO [18]. The configurations obtained from a reference heat transfer optimization problem are illustrated in Figure 4. These configurations were derived for a domain measuring 20 mm x 40 mm, subjected to a uniform heat source of 10 kW/m², with a maximum mesh size of 0.5 mm and a volume fraction of 0.3, corresponding to 30% solid material relative to the total domain. The density filter and Heaviside projection were utilized to ensure clear identification of solid boundaries. The diffusion coefficient for the Helmholtz filter was set to 6 times the mesh size, with the projection steepness and projection point adjusted to 8 and 0.5, respectively. For the transition between the thermal conductivity of voids and solids, a SIMP interpolation was applied, with a conductivity ratio of 470 and an interpolation exponent of 4. The choice of filter size influences the resulting geometry: increasing the filter size eliminates smaller elements, thereby affecting the number, thickness, and length of the branches in the structure. As shown in Figure 4, these configurations were used as starting points to generate fractal-based structures. A script was developed to construct a recursive fractal tree structure, controlled by key parameters including initial branch length and thickness, branching angles, the number of levels, branches per level, and the rotation angle at each iteration. To mathematically model the growth of the fractal, we define $\boldsymbol{l}_0, \boldsymbol{t}_0, \boldsymbol{\alpha}_0$ and $\boldsymbol{n}_0$ as the initial length and thickness of the branches, the branching angle, and the number of branches at the first level, respectively. These parameters govern the recursive relationships that guide the evolution of the fractal structure, enabling the generation of configurations with varying geometric and thermal properties. The recursive relations, applicable at each level, are as follows:

$$
\begin{aligned}
l_k &= l_{k-1} \cdot s_l \\
t_k &= t_{k-1} \cdot s_t \\
\alpha_k &= \alpha_{k-1} + \Delta\alpha \\
n_k &= n_0
\end{aligned}
\tag{1}
$$

where s_l is the scaling factor for length, s_t is the scaling factor for thickness, $\Delta\alpha$ represents the angle variation between levels, and n_0 can be either constant or variable. These scaling rules highlight the self-similar nature of fractal trees, where each branch is a scaled-down version of its predecessor, thus contributing to the overall complexity of the structure.

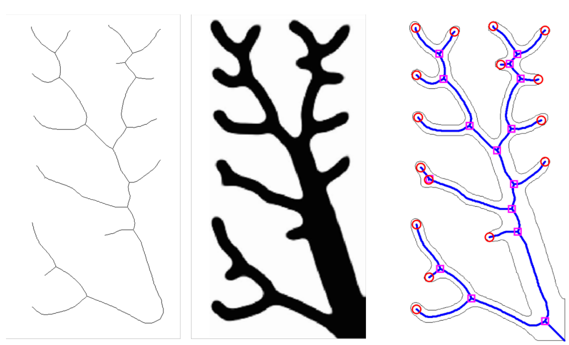
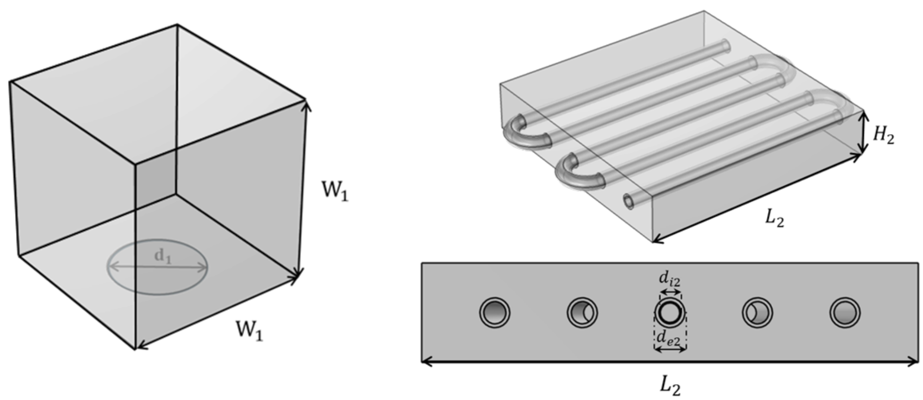


Fig. 4: Classification of branching features for TO-design.

3. Case Studies

In the first case, a circular chip with a diameter ($\boldsymbol{d}_1$) of 100 mm is subjected to a heat flux ($\dot{\boldsymbol{q}}$) of 2890 W/m². The chip is positioned at the center of a 200 x 200 x 200 mm cubic domain filled with PCM, as illustrated in Figure 5.a. In the second case, the system involves a latent heat thermal energy storage unit, with the domain featuring a square cross-section of side length (L_2) of 200 mm and height (H_2) of 40 mm. Inside this domain, a circular aluminium tube is placed, with an inner diameter (d_2) of 9 mm and thickness (t_2) of 1.5 mm. The serpentine tube runs through the domain five times, with water flowing inside it. The inlet temperature of the water (T_{in}) is 55°C, its specific heat (C_p) is 4.19 kJ/kg·K, and its density (ρ) is 997 kg/m³. The entire domain is filled with PCM, as shown in Figure 5.b. The thermophysical properties of the PCM used in both cases are summarized in Table 1. Introduced these cases we worked on the integration of TO within PCM models, solved through finite element simulations. For the phase change material, a simplified predictive model was employed. In the first configuration, a 3D analysis was conducted with a computational topology domain of 150 × 150 × 150 mm³, subjected to a uniform heat source of 2890 W/m², applied within the circular chip.



(a) (b)

Fig. 5: Case studies: electronic cooling (a), serpentine tube for LHTES (b).

Table 1: Thermophysical properties of PCM

Status	Specific Latent Heat (kJ/kg)	k (W/m·K)	ρ (kg/m³)	*Volume Expansion (%)*	*T (°C)*
Solid	165 (± 7.5%)	0.200	880	12.5	38
Liquid			760	12.5	42

The maximum mesh size was set to 0.3 mm, and the volume fraction of 0.1, corresponding to 10% solid material related to the total domain volume. To ensure a well-defined solid boundary, a density filter was applied, with a Helmholtz filter set to six times the mesh size. The transition between the thermal conductivities of the void and solid phases was modeled using the Solid Isotropic Material with Penalization (SIMP) interpolation, with a conductivity ratio of 650 and an interpolation exponent (n) of 4, as shown in Eq.2.

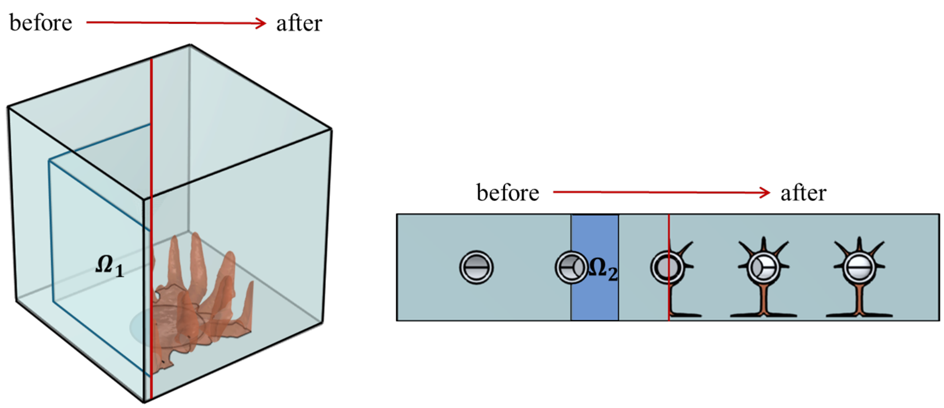
$$k = k_l + \theta^n \cdot (k_{sol} - k_l) \quad (2)$$

In the second case, a 2D analysis was performed with a domain size of 40 × 17.66 mm, where heat flux was applied along the perimeter of the external tube. The maximum mesh size was set to 0.4 mm, and a density filter was applied, with the Helmholtz filter ranging from four to six times the mesh size. The volume fraction of solid material was set to 5% relative to the total domain volume. As in the first case, SIMP interpolation was used to model the transition between the thermal conductivities of the void and solid phases, with identical parameters.

4. Preliminary Results and discussion

This section presents preliminary results for the topology optimization with phase change materials (TO-PCM), showcasing the designs obtained for electronic cooling and for latent heat thermal energy storage applications. For both cases the simulation results were obtained by minimizing the overall temperature in the domain as reported in Eq.2.In this equation $\boldsymbol{\theta}$ is the design variable of the material and the void which can take any value between 0 and 1. Figure 6.a shows the design for the first-mentioned case. According to this figure, the left side highlights the domain $\boldsymbol{\Omega}_1$, where the topology optimization was performed, while the right side presents the resulting design. It is important to emphasize that, due to the symmetry of the problem, the other half of the domain exhibits the same configuration. In addition, we can see that the material is distributed in such a way as to improve heat transfer, there is material at the base given the initial conductive heat transfer, next we see how it develops upward by effectively exploiting the natural convection mechanisms that occur during PCM melting. Similarly, in Figure 6.b, the difference between the initial and optimized configurations shows, highlighting the domain $\boldsymbol{\Omega}_2$, where the optimization was conducted. In this case as well, the material is symmetrically arranged with respect to the axis, with a higher concentration in the lower region of the domain due to the influence of natural convection-driven fluid motion.

$$minimize: f(\theta) = \int T(\theta)dV \tag{3}$$



(a) (b)

Fig. 6: Topology optimization results: electronic cooling (a), serpentine tube for LHTES (b).

The obtained design will be experimentally tested to evaluate its performance within the PCM. Numerical results show a promising trend in the melting fronts, with a total melting of the PCM in few minutes for the LHTES under the same boundary conditions used for the topology optimization. While, in the case of electronic cooling, a temperature mitigation is observed.

5.Conclusions

This paper presents preliminary results from the ongoing VISIONS project, which aims to develop high-performance thermal systems by integrating topology optimization with computational fluid dynamics. The project focuses on two primary applications: advanced electronic cooling and latent heat thermal energy storage using phase change materials (PCMs). The proposed approach facilitates the design of efficient and manufacturable architectures, particularly suited for additive manufacturing. The main conclusions are summarized as follows. An optimal heat sink design was achieved for electronic cooling, demonstrating that the combined use of TO and CFD with PCMs can effectively mitigate thermal hotspots. A serpentine topology-optimized finned tube array was designed using methodologies developed in previous project activities. This configuration, applied to LHTES systems, has shown enhanced thermal performance. Future work will focus on the fabrication of optimized prototypes using AM techniques, followed by experimental testing under varying operating conditions.

Acknowledgment

This work was supported by the Italian Government MUR Grant No. P2022NYPHL – PRIN 2022 PNRR "VISIONS: eVolutIonary deSign of InnOvative heat traNsfer deviceS" – Funded by European Union – Next Generation EU, Mission 4, Component 1, CUP: F53D23009800001.

References

[1] Bretado-de los Rios, M. S., Rivera-Solorio, C. I.,Nigam, K. D. P. (2021). An overview of sustainability of heat exchangers and solar thermal applications with nanofluids: A review. *Renewable and Sustainable Energy Reviews*, *142*, 110855.

[2] Moon, H., Miljkovic, N., King, W. P. (2020). High power density thermal energy storage using additively manufactured heat exchangers and phase change material. *International Journal of Heat and Mass Transfer*, *153*, 119591.

[3] Huang, C., Cai, W., Wang, Y., Liu, Y., Li, Q., Li, B. (2019). Review on the characteristics of flow and heat transfer in printed circuit heat exchangers. *Applied Thermal Engineering*, *153*, 190-205.

[4] Ahmed, H. E., Salman, B. H., Kherbeet, A. S., Ahmed, M. I. (2018). Optimization of thermal design of heat sinks: A review. *International Journal of Heat and Mass Transfer*, *118*, 129-153.

[5] Sarbu, I., Dorca, A. (2019). Review on heat transfer analysis in thermal energy storage using latent heat storage systems and phase change materials. Int J Environ Res, 43(1), 29-64.

[6] Feng, S. S., Kuang, J. J., Lu, T. J., Ichimiya, K. (2015). Heat transfer and pressure drop characteristics of finned metal foam heat sinks under uniform impinging flow. *Journal of Electronic Packaging*, *137*(2), 021014.

[7] Jouhara, H., Żabnieńska-Góra, A., Khordehgah, N., Ahmad, D., Lipinski, T. (2020). Latent thermal energy storage technologies and applications: A review. *International Journal of Thermofluids*, *5*, 100039.

[8] Hassan, F., Jamil, F., Hussain, A., Ali, H. M., Janjua, M. M., Khushnood, S., Li, C. (2022). Recent advancements in latent heat phase change materials and their applications for thermal energy storage and buildings: A state of the art review. *Sustainable Energy Technologies and Assessments*, *49*, 101646.

[9] Bianco, N., Busiello, S., Iasiello, M., Mauro, G. M. (2021). Finned heat sinks with phase change materials and metal foams: Pareto optimization to address cost and operation time. *Applied Thermal Engineering*, *197*, 117436.

[10] Shi, C., Wang, M., Yang, J., Liu, W., Liu, Z. (2021). Performance analysis and multi-objective optimization for tubes partially filled with gradient porous media. *Applied Thermal Engineering*, *188*, 116530.

[11] Ambrosio, G., Bianco, N., Chiu, W. K., Iasiello, M., Naso, V., Oliviero, M. (2016). The effect of open-cell metal foams strut shape on convection heat transfer and pressure drop. *Applied Thermal Engineering*, *103*, 333-343.

[12] Dbouk, T. (2017). A review about the engineering design of optimal heat transfer systems using topology optimization. Appl Therm Eng, 112, 841-854.

[13] Pietropaoli, M., Montomoli, F., Gaymann, A. (2019). Three-dimensional fluid topology optimization for heat transfer. *Structural and Multidisciplinary Optimization*, *59*, 801-812.

[14] Pizzolato, A., Sharma, A., Maute, K., Sciacovelli, A., Verda, V. (2017). Design of effective fins for fast PCM melting and solidification in shell-and-tube latent heat thermal energy storage through topology optimization. *Applied Energy*, *208*, 210-227.

[15] Fawaz, A., Hua, Y., Le Corre, S., Fan, Y., Luo, L. (2022). Topology optimization of heat exchangers: A review. Energy, 252, 124053.

[16] N. Bianco, A. Fragnito, M. Iasiello, G. M. Mauro. (2025), A simplified reduced order model to predict phase change materials heat transfer including natural convection, 10th Thermal and Fluids Engineering Conference (Hybrid), George Washington University, Washington, DC, USA.

[17] Li, B., Hong, J., Ge, L. (2017). Constructal design of internal cooling geometries in heat conduction system using the optimality of natural branching structures. International Journal of Thermal Sciences, 115, 16-28.
[18] N. Bianco, A. Fragnito, M. Iasiello, G. M. Mauro. (2025), Branching generative design to codify topology-optimized heat conduction structures, 10th Thermal and Fluids Engineering Conference (Hybrid), George Washington University, Washington, DC, USA.