

Potential application of phase change materials for thermal management system of next generation aircraft

Original

Potential application of phase change materials for thermal management system of next generation aircraft / Revello, Elisa; Monteverde, ALESSANDRO HUGO ANTONIO; Acerra, Francesco; Boccaccio, Marco. - ELETTRONICO. - (2024). (Intervento presentato al convegno 34th Congress of the International Council of the Aeronautical Sciences tenutosi a Firenze (ITA) nel 9-13 Settembre 2024).

Availability:

This version is available at: 11583/2994523 since: 2024-11-18T14:44:54Z

Publisher:

ICAS

Published

DOI:

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)



Potential application of phase change materials for thermal management system of next generation aircraft

Elisa Revello^{a*}, Marco Boccaccio^b, Francesco Acerra^c, Alessandro Monteverde^a

^aDepartment of Applied Science and Technology, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

^bLeonardo Labs, OGR Tech, C.so Castelfidardo 22, 10138 Torino, Italy

^cLeonardo SpA, Via dell'Aeronautica, 80038 Pomigliano d'Arco, Italy

*Corresponding author: elisa.revello@polito.it

Abstract

Next generation aircrafts are currently investigated to allow a significant reduction in the quantities of greenhouse gases emitted in the aviation sector. Thermal Management System (TMS) is a crucial aspect in the aeronautical field, where compactness and lightness are necessary due to the limited space and the need not to increase the required propulsive power. Among the possible solutions for temperature-sensitive applications are Phase Change Materials (PCMs), materials that undergo a phase change in the temperature range desired for heat storage, under form of latent heat. Their behavior can potentially be exploited to absorb occasional peak loads or anomalies of the next generation aircraft TMS. Depending on their chemical composition, solid-liquid PCMs can be organic, inorganic and eutectics. With the aim of studying and optimizing the spatial and temporal behavior of specific PCMs, a 1-D analytical model has been developed using a commercial software. The model is applied to determine the temperature profile and the variation of the melting front position during time along the PCM. A dynamic sizing analysis of several PCMs is proposed and their performances evaluated varying the initial solid wall temperature.

Keywords: Thermal Management; Next generation aircrafts; Phase Change Materials; Latent heat

1. Introduction

Next generation aircrafts are emerging as a challenging option to achieve a significant reduction of greenhouse gases (GHG) emitted in the aviation field, which is responsible for approximately 2% of global CO₂ emissions. To reach the net zero emissions (NZE) scenario by 2050, the EU is working with the international community to develop globally usable measures. [1] Moreover, the following strategies are identified by the next generation aircraft roadmap: integrate new avionics systems and additional electrical components, promote sustainable aviation fuels (SAFs) production and blending capacity, reduce in-flight energy through investments in new propulsion systems, and recapture emitted CO₂ emissions. [2] Historically, new generation aircrafts have led to a 20% reduction in energy consumption compared to the aircrafts they replace. [3]

Mainly there are three possible candidates to replace conventional aviation fuels: SAFs, hydrogen and batteries. One of the most promising solutions is the hydrogen-powered fuel cell (FC) system as it could meet the aeronautic requirements of compactness and lightness, which are fundamental in order not to increase the propulsive power required. The electrification of the traditional internal combustion engine with electrically-powered systems relies on large and high-power electrical equipment (e.g., fuel cell system, batteries, electrical motors, converters, power electronics, and others) that dissipate a large amount of heat [4]. For a high efficiency system, the electric loads are supplied from power buses by using power converters. The high-power density converters reflect into additional volume and weight required [5]. Thus, the cooling system must be able to cope with the progressively increasing demand of thermal loads without adding too much burden to the overall weight and size of these systems [6].

Still, there are several crucial challenges to be addressed in the early design stages to achieve the benefits of next generation aircrafts in terms of sustainable aviation. First, the design of thermal management system (TMS) to dissipate the heat released by the overheated components, which strongly affects the overall energy consumption and has a direct impact on realizing durability, cost, and performance targets required for an effective electrified aircraft. Therefore, the major design goal of TMS is to minimise its on board impact, lowering cooling drag and fuel penalty, allowing each component/subsystem to operate within a safe temperature range, by managing heat transfer between heat sources and heat sinks [7]. Moreover, the high power density energy storage and the efficient power management system for balancing power requirements between electric motors, combustion engines, and other auxiliary equipment should be optimized [8].

1.1 Background of TMS

In this section, a brief overview of the main heat transfer technologies and TMS architectures is provided. Since the thermal management system have gained significant attention from the scientific community, researchers have recently made concerted efforts to synthesize the exploration of relevant technologies through several review articles.

Generally, there are two available heat removal techniques: active cooling (using air, liquid, and phase change) and passive cooling (using heat pipes and heat spreaders), or in addition a hybrid cooling system (combining the above methods). Coutinho et al. [9] recently reviewed the developments in TMS for next generation aircrafts, pinpointing the most reliable TMS technologies for heat transfer with a medium/high TRL (>3-4) in the aeronautical field, as follows:

- Liquid cooling systems;
- Air/steam cooling cycles;
- Forced air cooling (ram air heat exchanger);
- Pumped two phase systems;
- Integrated heat exchangers (skin heat exchanger);
- Phase Change Materials (PCMs);

- Absorption refrigerators;
- Thermoelectric effects;
- Passive cooling systems.

Direct liquid cooling methods rely on the use of a coolant (typically water, which has a specific heat coefficient which is around four times that of air) to extract heat from the heat source. These technologies are the most consolidated and mature (TRL>7), together with air cooling systems. Particularly, air cooling (using natural and forced convection) is the simplest option since it does not require any additional equipment and there is no risk of leakage. However, it has a low thermal efficiency, due to the small heat capacity of air that makes it difficult to achieve temperature uniformity of the component [10]. Furthermore, air cooling is less effective during take-off and ground operating mode, since during periods of high power large amount of air is required. Thus, natural and forced convection could not be sufficient to dissipate abundant heat generated especially from high power components. Compared to air, liquid cooling method emerges to be more effective in heat transfer with a better temperature distribution. However, the need for more space increases system complexity, power consumption and cost, so it can outweigh the merits [11].

Conversely to active cooling, hybrid system using phase change materials (PCMs) are emerging as potential cooling strategies (TRL>4-5 [12]) due to their simple structure, high reliability, and no extra energy consumption, as detailed in section 1.2. This study focuses on the investigation of PCMs as innovative cooling, as reported in section 1.3. Typically, air cooling and passive cooling are suitable for small-medium scale (<5-10 kW), instead liquid and PCMs cooling could be a promising solution for high power levels (>10 kW) [13].

Regarding TMS architectures, Heerden et al. [14] provided an extensive overview of the main TMS in a conventional aircraft. Ram air (RA) heat exchangers are widely employed thanks to their simplicity and effectiveness; specifically, RA cooling exploits the dynamic pressure generated by the movement of the aircraft to ingest air into a duct. The air is then sent to directly cool down the devices or it can be transferred to a ram air heat exchanger. Despite the advantages, RA system generates significant cooling drag which should be minimized and additionally, during stationary or low speeds travel conditions, a fan is required to pull in air. Engine fan air (EFA) is another cooling method which consists of using atmospheric air on gas turbine propelled aircraft to dissipate the heat to the engine bypass air. To overcome momentum losses and avoid performance degradation, a surface/skin heat exchanger (SHX) could be adopted. An SHX system rejects the waste heat through the skin of the wing, fuselage, or other aircraft surfaces, which are in contact with the atmospheric air. In addition, the cooling capabilities of heat exchangers can be enhanced improving the heat transfer mechanism and lowering the pressure drops. Several techniques have been reported in the literature. The use of fins which allows the creation of new geometries, the introduction of microchannels characterized by small hydraulic diameter which increase the heat transfer surface area and the use of new manufacturing techniques, such as additive manufacturing (AM). Particularly, the outstanding benefits of HX enabled with AM include optimized geometries with improved surfaces, controlled surface roughness, fully controlled and organized porous structures, eliminating the need for welding or brazing, as reported in various works [15], [16], [17]. On the other hand, there are some challenges to overcome to achieve the full benefits of AM technologies. In another review article, Srinath et al. [18] explored TMS architectures proposed for hydrogen-powered propulsion technologies. A combination of TMS with the engine fuel system, and potentially compressor intercooling, turbine air cooling heat exchanger, and flow expander has been suggested by the authors as one of the future architectures for next generation aircraft. Most of the technologies previously described are used in the current research projects on TMS architectures for electrified aircraft propulsion, as summarized in another study of Coutinho et al. [7]. In a recent article published by Asli et al. [19] a classification of heat exchangers based on several criteria and a description of new emerging technologies in HX design, which is beyond the scope of this work, are provided. In particular, the authors have highlighted three main areas where heat exchangers are used in the next generation aircrafts,

including the propulsion cycle, environmental control system (ECS) and the TMS.

1.2 Phase Change Materials overview

Phase Change Materials are latent heat storage materials that undergo a phase transition between solid and liquid that occurs isothermally upon melting or solidifying. During phase transition, as pictured in **Figure 1**, the PCM stores thermal energy in the form of latent heat by an endothermal process that dissolves the chemical bonds of PCM and release it exothermally when being cooled to recover its solid state.

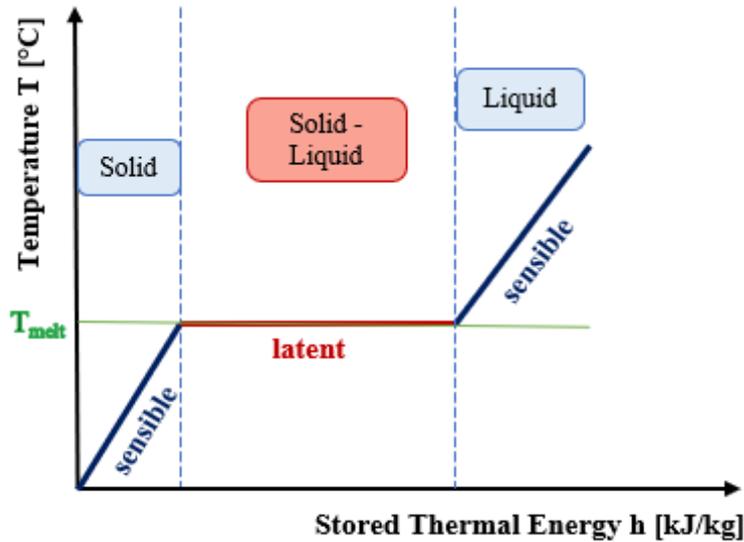


Figure 1. PCM phase change transition.

The total amount of energy absorbed by PCM (Q), which is the sum of the sensible and latent heat, can be calculated as follows:

$$Q = \int_{T_i}^{T_m} mc_{p,s}dT + m\Delta H + \int_{T_m}^{T_f} mc_{p,l}dT = m [c_{p,s}(T_m - T_i) + \Delta H + c_{p,l}(T_f - T_m)] \quad (1)$$

Where $c_{p,s}$ and $c_{p,l}$ are the specific heat of solid and liquid PCM, respectively, ΔH denotes the latent heat capacity, T_i , T_m and T_f represent the initial, melting, and final temperature, respectively [20]. PCMs can be classified into different categories based on their phase state, chemical composition or melting temperature, as reported in **Figure 2**.

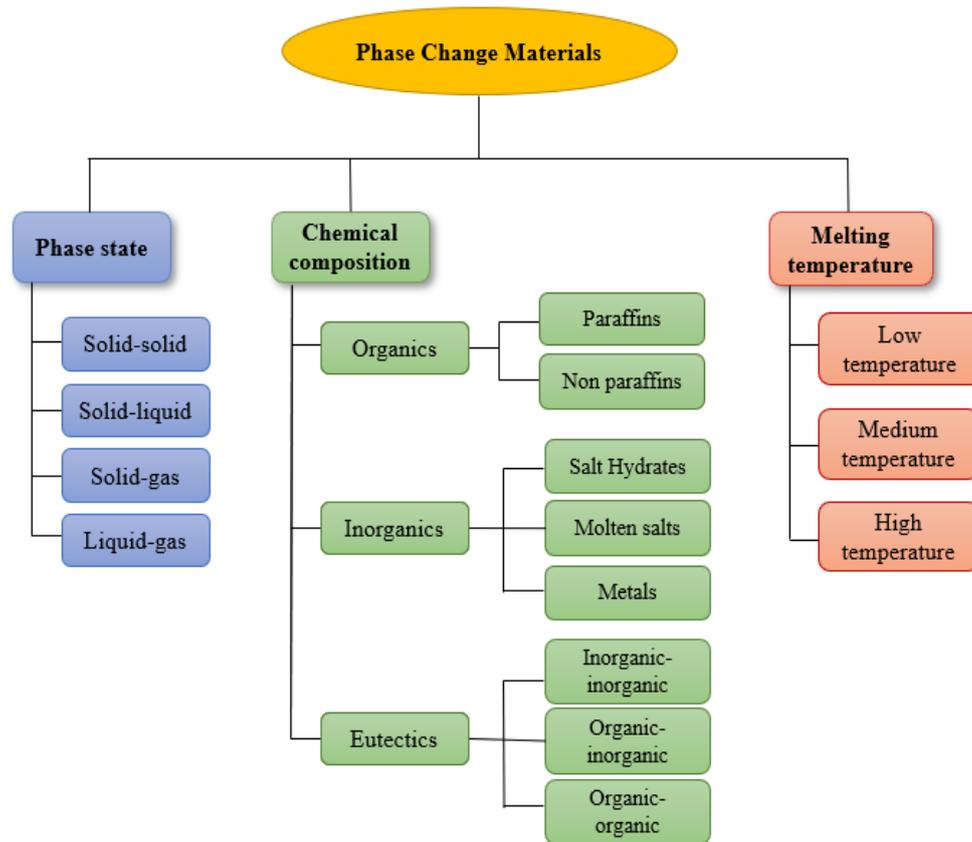


Figure 2. Classification of Phase Change Materials.

According to the desired range of operating temperature several type of PCMs with different melting temperature can be considered.

Organic PCMs can be paraffins and non-paraffin, the former involves fatty acids, alcohols, glycols and esters. They are rather stable, safe, and have a high latent heat of fusion (>180 kJ/kg). However, these compounds are also flammable, toxic and have a low thermal conductivity ($0.1\text{--}0.35$ W/(m·K)). Particularly, the enhancement in thermal conductivity acquired great attention recently.

Inorganic PCMs are composed of inorganic molecules, they are salts hydrates (most used), molten salts, and metals. Inorganic materials have attractive characteristics, not only they propose a wide melting temperature range ($>5\text{--}130$ °C), but they are also thermally safe and have a high latent heat rate (>220 kJ/kg). However, super cooling, phase segregation and lack of long-term stability of these materials still represent an issue; consequently, inorganic PCMs applications are limited as latent heat storage systems. This poor stability has been reported in the literature and result from two factors: poor stability of the materials properties itself due to thermal cycling, and/or corrosion between the PCM and the container.

Eutectic mixtures are a combination of two or more low melting temperature components of organics, inorganics, or both, compounds at specific atomic ratio of products at which the mixture melts. Due to this, they have more desired features such as a higher latent heat, a sharp melting point, and no super cooling and phase segregation phenomena [21], [22].

The widespread application of PCMs still faces challenges mainly related to the improvement of their low thermal conductivity and the growth of volume and liquid leaking after melting. Therefore, an effective PCM-based TMS should have high latent heat of fusion, high chemical stability over multiple cycles, compatibility with aeronautic materials and relatively low cost.

1.3 Aim of this work

This work aims to assess with a preliminary modelling analysis the potential application of PCMs, as thermal energy storage (TES) devices, to dampen thermal loads of the heat source [20]. On this matter, section 2 describes the methodology used to preliminary evaluate the thermal behaviour of a PCM with a simplified one-dimensional (1-D) analytical model developed on MATLAB.

In section 3 the main outcomes of the modelling analysis are discussed and finally the following section outlines the conclusion of this work.

Subsequently, a more accurate 3-D physical model will be implemented to characterise the phase change material in two concentric pipes with a heat transfer fluid, in order to compare a conventional cooling system with an innovative one based on PCM.

2. Methodology

This section details the phase change problem in a semi-infinite medium filled with a pure PCM, where the conduction heat transfer is 1-D transient, was formulated as a Stefan problem [23] and solved with an analytical solution [24] through a MATLAB script.

2.1 Geometry

The simplified geometrical configuration of the system analyzed (surface of the heat source covered by a layer of PCM) is schematized in **Figure 3.a**. Further, **Figure 3.b** pictures the melting process of the phase change material. H_{comp} is the height of the cylindrical component, R_{comp} its radius and R_{TOT} represents the system total radius. In addition, the interface between solid (PCM s) and liquid (PCM l) state of the material is highlighted with a red dashed line.

The sizing procedure of a PCM, according to the analytical solution of Neumann (section 2.3), is summarized in the logical diagram illustrated in **Figure 4**.

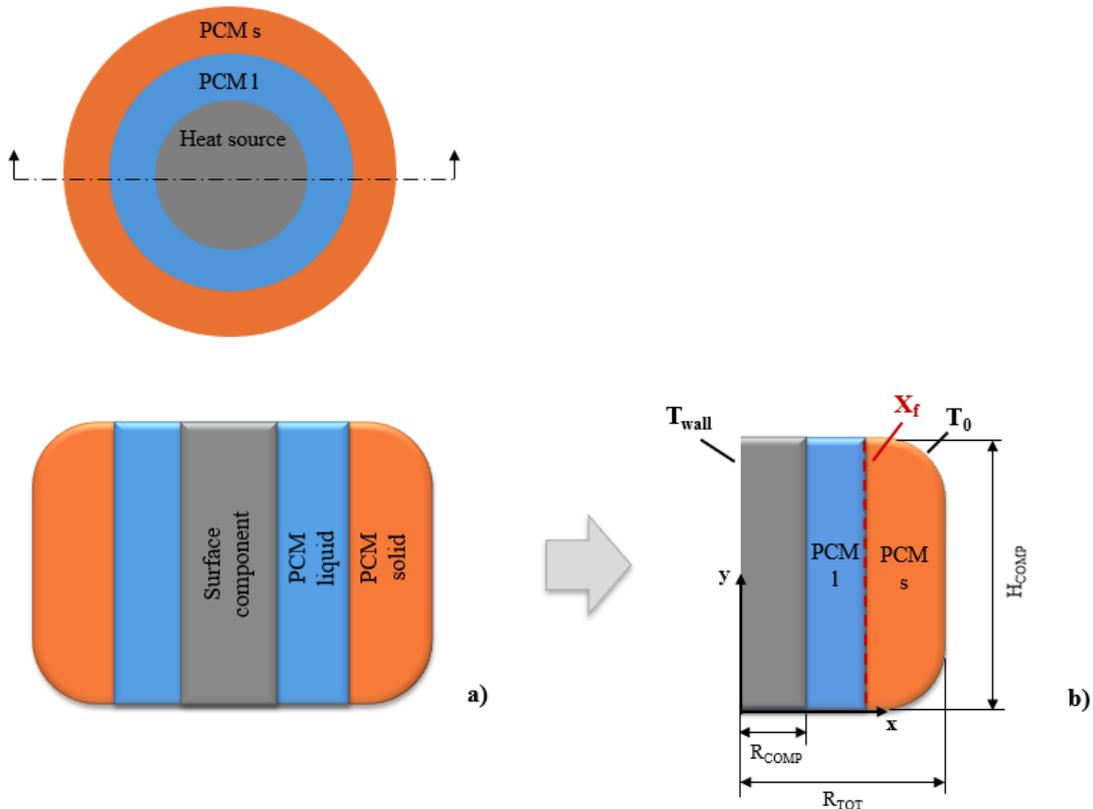


Figure 3. a) Top view (top) and cross-section (bottom) of the simplified geometric system. b) Scheme of PCM melting process.

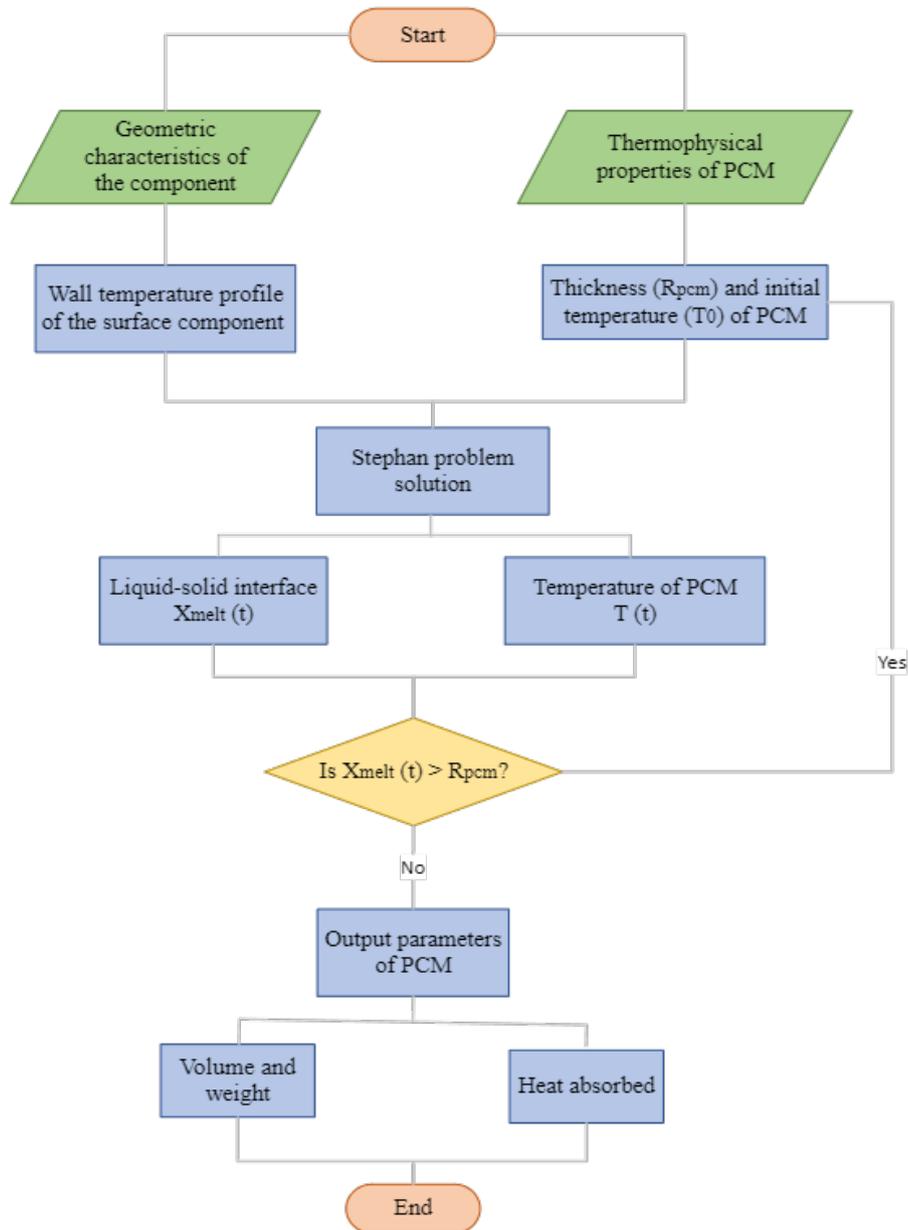


Figure 4. Logical diagram of the PCM sizing procedure.

2.2 Simplifying assumptions

The model is developed under the following simplifying assumptions :

- The PCM is considered as a perfectly pure, homogeneous and isotropic material;
- The phase change process is isothermal;
- The interface between the solid and liquid phases of the PCM is fine (surface);
- The thermophysical properties (i.e., specific heat capacity, density and heat conductivity) of the PCM are constant both in solid and liquid phases, but they may differ from phase to phase;
- Conduction in the PCM is the only heat transfer mechanism in the two phases (solid and liquid) and it is 1-D transient;
- Natural convection within the liquid phase and radiation are ignored.

2.3 Analytical solution

The energy conservation equations which govern the temperature variations in the liquid (subscript l) and solid (subscript s) phases are formulated respectively as:

$$\frac{\partial T_l}{\partial t} = \frac{\partial}{\partial x} \left(\alpha_l \frac{\partial T_l}{\partial x} \right), \quad 0 < x < X_f, t > 0 \text{ liquid phase} \quad (2)$$

$$\frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x} \left(\alpha_s \frac{\partial T_s}{\partial x} \right), \quad X_f < x, t > 0 \text{ solid phase} \quad (3)$$

In these formulations T refers to the temperature, t is the time, x represents the spatial coordinate in the melting process domain and α denotes the PCM thermal diffusivity, defined as:

$$\alpha = \frac{k}{\rho c_p} \quad (4)$$

Where k , ρ and c_p represent the thermal conductivity, the density, and the specific heat of PCM, respectively.

The initial conditions (at $t = 0$) applied are:

$$T_s(x, 0) = T_0, \quad 0 \leq x \leq R_{PCM} \quad (5)$$

$$X_f(0) = 0 \quad (6)$$

The boundary conditions (at $t > 0$) imposed are given by:

$$T_l(x = 0, t) = T_{wall} \quad (7)$$

$$T_l(x = X_f, t) = T_s(x = X_f, t) = T_{melt} \quad (8)$$

$$T_s(x \rightarrow \infty, t) = T_0 \quad (9)$$

Therefore, the temperature distributions for liquid and solid phases can be written with the following relationships:

$$\frac{T_l(x, t) - T_{wall}}{T_{melt} - T_0} = \frac{\operatorname{erf}\left(\frac{x}{2\sqrt{\alpha_l t}}\right)}{\operatorname{erf}(\xi)}, \quad 0 < x < X_f, t > 0 \text{ liquid phase} \quad (10)$$

$$\frac{T_s(x, t) - T_0}{T_{melt} - T_0} = \frac{\operatorname{erfc}\left(\frac{x}{2\sqrt{\alpha_s t}}\right)}{\operatorname{erfc}(v\xi)}, \quad X_f < x, t > 0 \text{ solid phase} \quad (11)$$

Where erf and erfc are the error function and the complementary error function built in MATLAB, respectively. v is the ratio between the PCM thermal diffusivity of the liquid or solid phase (α_i), expressed by: $v = \sqrt{\alpha_l/\alpha_s}$ and ξ is a constant parameter that can be obtained by solving a transcendental equation, which is a function of the Stephan number.

Thus, the temporal evolution of the liquid-solid interface (X_f) is defined as follows:

$$X_f(t) = 2\xi\sqrt{\alpha_l t} \quad (12)$$

Phase transition occurs when the melting/freezing time (t_{melt}) of the PCM is achieved. Consequently, the solid-liquid interface moves away from the heat transfer surface and the location of this moving zone is not known a priori. Thus, the solution of a phase change problem is not so easy, even when the heat transfer process is assumed to be conduction controlled. Analytical solutions for the estimation of t_{melt} are possible only for simple geometry and for simplified boundary conditions [25], [26]. These analytical solutions are expressed in terms of dimensionless phase transition time (t^*), which is defined according to the relationship:

$$t^* = \frac{\alpha_l t_{melt}}{R_{PCM}^2} \quad (13)$$

Where R_{PCM} is the PCM thickness. Additionally, for a cylindrical system the approximate solution of Solomon can be used to estimate t_{melt} :

$$t^* = 0.11 + \frac{0.25}{St_l} \quad (14)$$

Where St_l is the Stephan number for the liquid phase.

Finally, the volume (V_{PCM}) occupied by the material to store the thermal energy released is calculated with the equation:

$$V_{PCM} = \pi \left(\left(\frac{1}{2} D_{comp} + X_f(t_{melt}) \right)^2 - \left(\frac{1}{2} D_{comp} \right)^2 \right) \cdot H_{comp} \quad (15)$$

The mass of the PCM (m_{PCM}) is given by the product of the obtained volume by its density:

$$m_{PCM} = V_{PCM} \cdot \rho \quad (16)$$

With the aim of better understand and optimize the spatial and temporal behavior of the phase change material, a simulation campaign for several PCMs was performed in section 3 varying the initial wall temperature of a module, according to literature data concerning Li-ion batteries [27], [28], [29], [30].

3. Preliminary results and discussion

According to the sizing procedure illustrated in **Figure 4**, an estimation of mass and temperature distribution along the PCM has been evaluated. The PCMs selected for this preliminary analysis are reported in **Table 1**.

Table 1. Main properties of PCMs considered.

| PCM | Specific heat capacity, kJ/(kg K) | | Density, kg/m ³ | | Heat conductivity, W/(m K) | | Melting point, °C | Heat storage capacity, kJ/kg |
|-------------------------------------|-----------------------------------|-----------|----------------------------|----------|----------------------------|-------|-------------------|------------------------------|
| | $c_{p,s}$ | $c_{p,l}$ | ρ_s | ρ_l | k_s | k_l | | |
| <i>Abbreviation</i> | | | | | | | T_{melt} | L |
| Paraffin wax RT18HC [31] | 2 | 2 | 880 | 770 | 0.2 | 0.2 | 18 | 260 |
| Paraffin wax RT70HC [32] | 2 | 2 | 880 | 770 | 0.2 | 0.2 | 70 | 260 |
| Urea-KCl [23] | 1.69 | 1.96 | 1370 | 1370 | 0.83 | 0.66 | 115 | 227 |
| Magnesium chloride hexahydrate [23] | 2 | 2.4 | 1570 | 1570 | 0.7 | 0.58 | 117 | 150 |

In addition, a PCM thickness of 0.05 m and 263 K as initial temperature of the PCM are the assumptions for this preliminary assessment. By applying an initial wall temperature profile of the component to be cooled down, the model can be useful to analyse and compare the thermal behaviour of different PCMs.

Figure 5 evidences in blue the temperature profile simulated for the considered heat source, the melting temperature of the magnesium chloride hexahydrate (salt hydrate) is pictured in green, while the orange curve represents the evolution of the solid-liquid interface. Notably, the temperature rising inside the module ranges from a typical operating temperature (298 K) to a dangerous condition (400 K) which is critical for safety issues, resulting in failure of the component. As shown in **Figure 5**, when the melting temperature is reached and the phase transition takes place, the melting front position

changes leading to the PCM storing heat.

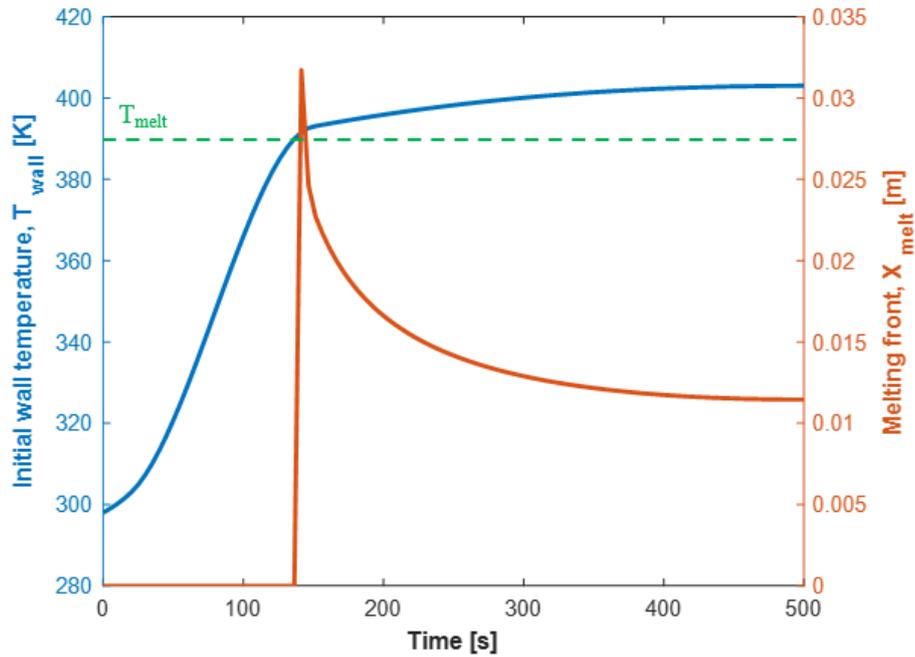


Figure 5. Salt Hydrate PCM: Wall temperature profile (blue curve), melting front evolution (orange curve) and melting temperature (green dashed line).

Table 2 shows the results obtained from the adopted modelling approach. In particular, the salt hydrate stands out to potentially absorb higher amounts of thermal power compared to the other PCMs considered. This might be related to its higher thermal conductivity respect to the two paraffins; however, an increase in the thermal conductivity of PCM lead to a decrease in the latent heat of phase change material and subsequently to a higher mass value.

Table 2. Output results from MATLAB model.

| Output parameter | Paraffin RT18HC | Paraffin RT70HC | Urea-KCl | Magnesium chloride hexahydrate |
|---|-----------------|-----------------|----------|--------------------------------|
| Mass, kg | 3.092 | 5.298 | 9.033 | 8.314 |
| Volume, m ³ | 0.004 | 0.006 | 0.007 | 0.005 |
| Thermal power absorbed in Δt , kW | 0.111 | 1.035 | 5.203 | 15.418 |

4. Conclusion and future work

The electrification of aircrafts offers a viable solution to address the limitations posed by the relatively low energy densities of batteries in fully electric aviation. However, this technical strategy results in increase of electric loads compared to traditional aircraft system. Effective and compact thermal management system is a critical challenge in next generation vehicles. To maintain high performances and homogeneous temperature distribution over time of the critical components, an efficacious TMS of heat sources should be designed. Therefore, several cooling methods (i.e., active, passive and hybrid) are investigated to guarantee the heat dissipation.

This study provides a general background of TMS architectures and technologies, with a focus on PCMs as cooling solution. Moreover, this work aims to assess through a simplified 1-D modelling analysis the potential use of PCMs to dampen the thermal peaks of a heat source of a next generation aircraft. Preliminary results reveal that a salt hydrate may be more efficient than common paraffins in dissipating the heat produced by the surface of the overheated component and this could be mainly

due to its higher thermal conductivity.

From the perspective of practical application, TMS uses PCM could not purely rely on PCM cooling. Particularly, composite PCM with higher energy density values (ranges between 100 and 200 kJ/kg) compared to pure PCM should be preferred [33]. A hybrid system that integrates both PCM and liquid cooling should be the optimal choice for removing heat from the heat source. This solution combines the advantages of active and passive cooling, which provides temperature uniformity, saving electrical consumption and with relatively high cooling efficiency.

Further in-depth modelling analysis will be devoted to a comprehensive understanding of the thermal behavior of a phase change material, to maintain the temperature of the heat source in the design criteria range. To this end, a 3-D physical model will be developed to characterize the PCM in two concentric pipes with a heat transfer fluid, in order to compare a conventional cooling system with an innovative one based on PCM.

5. Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.

Acknowledgements

This project has received funding from the NextGeneration EU 2022 research and innovation programme under DM 352 (CUP No E12B22000520006) of National Recovery and Resilience Plan (PNRR) and it is financially supported by Leonardo S.p.A. Authors would also like to thank the institution Politecnico di Torino and Ministry of University and Research (MUR) for the opportunity.

References

- [1] IEA, "Tracking Clean Energy Progress 2023." Accessed: Jan. 09, 2024. [Online]. Available: <https://www.iea.org/energy-system/transport/aviation#tracking>
- [2] International Air Transport Association, "Energy and New Fuels Infrastructure." Accessed: Jan. 09, 2024. [Online]. Available: <https://www.iata.org/en/programs/environment/sustainable-aviation-fuels/>
- [3] International Air Transport Association, "Aircraft Technology Roadmap." Accessed: Jan. 09, 2024. [Online]. Available: <https://www.iata.org/en/programs/environment/roadmaps/>
- [4] W. Affonso *et al.*, "System architectures for thermal management of hybrid-electric aircraft - FutPrint50," *IOP Conf Ser Mater Sci Eng*, vol. 1226, no. 1, p. 012062, Feb. 2022, doi: 10.1088/1757-899x/1226/1/012062.
- [5] A. Sakanova, C. F. Tong, A. Nawawi, R. Simanjorang, K. J. Tseng, and A. K. Gupta, "Investigation on weight consideration of liquid coolant system for power electronics converter in future aircraft," *Appl Therm Eng*, vol. 104, pp. 603–615, Jul. 2016, doi: 10.1016/j.applthermaleng.2016.05.097.
- [6] M. Reyes, D. Alonso, J. R. Arias, and A. Velazquez, "Experimental and theoretical study of a vapour chamber based heat spreader for avionics applications," *Appl Therm Eng*, vol. 37, pp. 51–59, May 2012, doi: 10.1016/J.APPLTHERMALENG.2011.12.050.
- [7] M. Coutinho *et al.*, "A Study on Thermal Management Systems for Hybrid–Electric Aircraft," *Aerospace*, vol. 10, no. 9, Sep. 2023, doi: 10.3390/aerospace10090745.
- [8] J. Benzaquen, J. B. He, and B. Mirafzal, "Toward More Electric Powertrains in Aircraft: Technical Challenges and Advancements," *CES Transactions on Electrical Machines*

- and *Systems*, vol. 5, no. 3, pp. 177–193, Sep. 2021, doi: 10.30941/CESTEMS.2021.00022.
- [9] M. Coutinho *et al.*, “A review on the recent developments in thermal management systems for hybrid-electric aircraft,” *Applied Thermal Engineering*, vol. 227. Elsevier Ltd, Jun. 05, 2023. doi: 10.1016/j.applthermaleng.2023.120427.
- [10] G. H. Kim and A. Pesaran, “Battery Thermal Management System Design Modeling,” 2006. [Online]. Available: <http://www.osti.gov/bridge>
- [11] A. A. H. Akinlabi and D. Solyali, “Configuration, design, and optimization of air-cooled battery thermal management system for electric vehicles: A review,” *Renewable and Sustainable Energy Reviews*, vol. 125. Elsevier Ltd, Jun. 01, 2020. doi: 10.1016/j.rser.2020.109815.
- [12] W. Affonso *et al.*, “Thermal management challenges for HEA – FUTPRINT 50,” in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing Ltd, Jan. 2021. doi: 10.1088/1757-899X/1024/1/012075.
- [13] S. Tiwari, M. J. Pekris, and J. J. Doherty, “A review of liquid hydrogen aircraft and propulsion technologies,” *International Journal of Hydrogen Energy*, vol. 57. Elsevier Ltd, pp. 1174–1196, Feb. 29, 2024. doi: 10.1016/j.ijhydene.2023.12.263.
- [14] A. S. J. van Heerden, D. M. Judt, S. Jafari, C. P. Lawson, T. Nikolaidis, and D. Bosak, “Aircraft thermal management: Practices, technology, system architectures, future challenges, and opportunities,” *Progress in Aerospace Sciences*, vol. 128. Elsevier Ltd, Jan. 01, 2022. doi: 10.1016/j.paerosci.2021.100767.
- [15] J. Y. Ho, K. C. Leong, and T. N. Wong, “Additively-manufactured metallic porous lattice heat exchangers for air-side heat transfer enhancement,” *Int J Heat Mass Transf*, vol. 150, p. 119262, Apr. 2020, doi: 10.1016/J.IJHEATMASSTRANSFER.2019.119262.
- [16] I. Kaur and P. Singh, “State-of-the-art in heat exchanger additive manufacturing,” *Int J Heat Mass Transf*, vol. 178, p. 121600, Oct. 2021, doi: 10.1016/J.IJHEATMASSTRANSFER.2021.121600.
- [17] S. A. Niknam, M. Mortazavi, and D. Li, “Additively manufactured heat exchangers: a review on opportunities and challenges,” *International Journal of Advanced Manufacturing Technology*, vol. 112, no. 3–4. Springer Science and Business Media Deutschland GmbH, pp. 601–618, Jan. 01, 2021. doi: 10.1007/s00170-020-06372-w.
- [18] A. N. Srinath *et al.*, “Thermal Management System Architecture for Hydrogen-Powered Propulsion Technologies: Practices, Thematic Clusters, System Architectures, Future Challenges, and Opportunities,” *Energies*, vol. 15, no. 1. MDPI, Jan. 01, 2022. doi: 10.3390/en15010304.
- [19] M. Asli *et al.*, “Thermal management challenges in hybrid-electric propulsion aircraft,” *Progress in Aerospace Sciences*, vol. 144. Elsevier Ltd, Jan. 01, 2024. doi: 10.1016/j.paerosci.2023.100967.
- [20] Y. Liu, R. Zheng, and J. Li, “High latent heat phase change materials (PCMs) with low melting temperature for thermal management and storage of electronic devices and power batteries: Critical review,” *Renewable and Sustainable Energy Reviews*, vol. 168. Elsevier Ltd, Oct. 01, 2022. doi: 10.1016/j.rser.2022.112783.
- [21] J. Jaguemont, N. Omar, P. Van den Bossche, and J. Mierlo, “Phase-change materials (PCM) for automotive applications: A review,” *Applied Thermal Engineering*, vol. 132. Elsevier Ltd, pp. 308–320, Mar. 05, 2018. doi: 10.1016/j.applthermaleng.2017.12.097.
- [22] Y. G. Lv, G. P. Zhang, Q. W. Wang, and W. X. Chu, “Thermal Management Technologies Used for High Heat Flux Automobiles and Aircraft: A Review,” *Energies*, vol. 15, no. 21. MDPI, Nov. 01, 2022. doi: 10.3390/en15218316.
- [23] M. Shi, M. Sanders, A. Alahmad, C. Perullo, G. Cinar, and D. N. Mavris, “Design and Analysis of the Thermal Management System of a Hybrid Turboelectric Regional Jet for the NASA ULI Program.”
- [24] L. Mansouri, M. Balistrrou, and B. Baudoin, “One-dimensional time-dependent modeling of conductive heat transfer during the melting of an initially subcooled semi-infinite PCM.” [Online]. Available: <https://hal.archives-ouvertes.fr/hal-03465225>

- [25] K. Rathod Manish and B. Jyotirmay, "Development of Correlation for Melting Time of Phase Change Material in Latent Heat Storage Unit," in *Energy Procedia*, Elsevier Ltd, 2015, pp. 2125–2130. doi: 10.1016/j.egypro.2015.07.339.
- [26] L. Kalapala and J. K. Devanuri, "Parametric investigation to assess the melt fraction and melting time for a latent heat storage material based vertical shell and tube heat exchanger," *Solar Energy*, vol. 193, pp. 360–371, Nov. 2019, doi: 10.1016/j.solener.2019.09.076.
- [27] H. Behi *et al.*, "Thermal management analysis using heat pipe in the high current discharging of lithium-ion battery in electric vehicles," *J Energy Storage*, vol. 32, Dec. 2020, doi: 10.1016/j.est.2020.101893.
- [28] M. S. Isfahani, A. Gharehghani, S. Saeedipour, and M. Rabiei, "PCM/metal foam and microchannels hybrid thermal management system for cooling of Li-ion battery," *J Energy Storage*, vol. 72, Nov. 2023, doi: 10.1016/j.est.2023.108789.
- [29] D. Karimi, H. Behi, J. Van Mierlo, and M. Berecibar, "An Experimental Study on Thermal Performance of Graphite-Based Phase-Change Materials for High-Power Batteries," *Energies (Basel)*, vol. 15, no. 7, Apr. 2022, doi: 10.3390/en15072515.
- [30] F. Zhang, L. Zhai, L. Zhang, M. Yi, B. Du, and S. Li, "A novel hybrid battery thermal management system with fins added on and between liquid cooling channels in composite phase change materials," *Appl Therm Eng*, vol. 207, May 2022, doi: 10.1016/j.applthermaleng.2022.118198.
- [31] Rubitherm, "RT 18HC datasheet." Accessed: May 06, 2024. [Online]. Available: <https://www.rubitherm.eu/produktkategorie/organische-pcm-rt>
- [32] Rubitherm, "RT 70HC." Accessed: May 06, 2024. [Online]. Available: <https://www.rubitherm.eu/produktkategorie/organische-pcm-rt>
- [33] Y. Zhao, B. Zou, J. Ding, and Y. Ding, "Experimental and numerical investigation of a hybrid battery thermal management system based on copper foam-paraffin composite phase change material and liquid cooling," *Appl Therm Eng*, vol. 218, Jan. 2023, doi: 10.1016/j.applthermaleng.2022.119312.

