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A review on the recent developments in thermal management systems for hybrid-electric aircraft

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ABSTRACT

The electrification of aircraft propulsive systems has been identified as one of the potential solutions towards a lower carbon footprint in the aviation industry. However, there are still several environmental and technological challenges associated with the propulsion electrification. One of these challenges is the development of adequate thermal management systems that are lightweight and can cope with the higher heat loads estimated for all-electric and hybrid-electric aircraft when compared with conventional architectures. Addressing this latter issue is therefore an operational requirement for more electric aircraft. There are several solutions proposed in the literature to tackle this challenge at different levels of development. The main focus of the current paper is to provide a critical review on the existing solutions. From this review, liquid cooling loops integrated with ram air heat exchangers seem to be the most viable ones with nowadays technology. However, in the future the introduction of nanofluids with higher thermal conductivities and skin heat exchangers can be an interesting solution to improve performance.

1. Introduction

To meet the environmental goals proposed in the FlightPath2050 document [1], the future aircraft designs will need to incorporate changes such as improvements in aerodynamic efficiency [2], lightweight structures [3], greener energy sources such as biofuels [4] and cryogenic fuels [5], trajectory optimization [6], and propulsive system electrification [7,8], among others.

The use of hybrid-electric propulsion that runs on both electricity and fuel is one of the approaches currently being studied [9–12].

However, electrifying the propulsion system introduces some environmental and technical challenges. The environmental ones are associated to the production and integration of batteries [13] or fuel cells [14]. Regarding the technical challenges, these are mainly related not only to the lower specific energy density of these electrochemical devices [15] but also to the integration of high-power electric components in the aircraft that generate high heat loads [16]. To cope with this latter issue, new thermal management strategies are mandatory when compared to current and conventional aircraft [17]. In a traditional aircraft the heat management consists typically in utilizing fluid systems (e.g., air, fuel, and oil) to extract excess heat generated within the various engine components and systems and employ this extracted heat for other purposes, besides improving engine performance [9]. Nevertheless, in a hybrid-electric aircraft the volume of fuel is reduced, and it might not be enough to keep all the on-board equipment within its operating temperature, e.g., batteries must operate at an ideal temperature, typically between 0 °C and 40 °C [18]. Furthermore, the lower thermal conductivity of lightweight composite structures when compared to conventional metallic structures aggravates this issue [19]. Thus, several different solutions for Thermal Management Systems (TMSs) have been explored as reported in a review paper by van Heerden et al. [16] on this thematic. In that article [16], the authors approach technological aspects and practices that can be used for the proper design of TMSs, including the corresponding architectures and components. Furthermore, they also discuss the environmental impact of such systems.

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Another aspect of this study concerns new technologies that may be used in the near future, such as new types of thermal reservoirs, Phase Change Materials (PCM), and new air recirculation strategies. In the article by Affonso et al. [20], different strategies, technologies and procedures that can be used in the thermal management system are shown. Affonso et al. [21] present a study on thermal management architectures for the three different propulsive systems considered for the aircraft of the FUTure PRopulsion & INTegration (FutPrInt50) project: (i) parallel hybrid using sustainable aviation fuel; (ii) parallel hybrid composed by liquid hydrogen gas turbine and electric motors powered by batteries and fuel cells; and (iii) serial hybrid with liquid hydrogen fuel cells and batteries. For these propulsive systems, they propose five different conceptual architectures combining different technologies: (i) liquid cooling loop with Vapor Cycle System (VCS); (ii) fuel-oil loop with liquid cooling and VCS; (iii) absorption refrigerator with evaporator, ram air and VCS; (iv) liquid hydrogen cooling with evaporator; and (v) cryogenic cooling with liquid hydrogen considering the reverse Brayton cycle as basis. In [22] a case study based on an Unmanned Aerial Vehicle (UAV) equipped with a thermal management system based on an air cycle machine is shown. Their methodology consists in generating several possible combinations between components and selecting candidate solutions from the resulting Pareto frontier. Venkategowda et al. [23] propose and explore an architecture for the TMS of a Boeing 787 aircraft engine for in-flight conditions using a spray cooling system.

Even though a considerable amount of work has been carried on this field, none of the cited or consulted references presents a TMS architecture that was optimized and could respond to a vast number of aircraft operating scenario. Only one type of architecture, that works well for a given scenario, is shown in these references. Thus, efficient TMS architectures that work optimally throughout the flight mission are desired for both hybrid and all-electric aircraft. With this goal in mind, the main objective of this document is to shed light on the recent efforts on TMSs, including components and architectures that may enable to reach such goal. To accomplish this goal, the document is organized as follows: (i) first, an introduction is given, where the TMS design problem and the main objective of this document are exposed (Section 1); (ii) followed by a brief overview of the heat transfer technologies, classified in a decreasing order of Technology Readiness Level (TRL) (Section 2); (iii) next, a description of the main recent TMS architectures reported in the literature is provided (Section 3); (iv) followed by the presentation of the current status, challenges and new trends on TMS (Section 4); and (v) finally, the concluding remarks drawn from this overview document are presented (Section 5).

2. Overview of technologies for heat transfer

In this section, an overview of the TMS technologies is presented. A summarized review is showed in Fig. 1.

Table 1 describes the main Heat Transfer Technologies (HTT) and briefly explores the main challenges and opportunities associated to them, identifying the present TRL [24] of each one.

3. Thermal management systems to enable hybrid-electric aircraft

The present section intends to provide a critical discussion on the recent efforts done in the field of thermal management to enable future commercial hybrid-electric aircraft. Each subsection addresses the key components to accomplish this goal, starting with batteries (Section 3.1), then electrical machines (Section 3.2), followed by combustion engines and fuel systems (Section 3.3), passing through environmental control system (Section 3.4), and ending with a proposed sizing methodology (Section 3.5).

3.1. Batteries

One of the main differences from a conventional aircraft and a future hybrid-electric one is the possible use of batteries as part of the powertrain. Battery Thermal Management System (BTMS) primary purpose is to keep the temperature of battery cells in a pack within a safe range. It contributes to the battery pack's longevity while also assuring its safe and secure functioning. BTMS can be used for cooling, heating, or insulating, depending on the operational and ambient circumstances [45]. The medium of a classic BTMS is air, which is mobilized by an electric blower or fan (air cooling). Other methods have also been proposed, including liquid cooling (using water, glycol, oil, acetone, refrigerants, etc.) and the cooling using PCM technologies. In this field, because of its high energy density and outstanding performance, Lithium-Ion Batteries (LIB) have sparked a considerable attention and most of the studies carried out use this type of batteries.

Considering an aircraft capable of carrying 76 passengers for 1,980 nautical miles (ULI Aircraft), Perullo et al. [46] proposed cooling the battery module by integrating it with the current Environmental Control Systems (ECS), so that any surplus air cooling capacity from the ECS could be exploited. It was established that, by operating at its maximum speed during all flight, the existing ECS is adequate to maintain the battery below the temperature limit because of the battery's high thermal inertia. With this, the ECS has no mass penalty, but it does have a 1.4% block fuel burn penalty due to the increased engine bleed air and ram air necessary to run it at maximum speed. The overall TMS can be found in Fig. 2.

Six thermal management options have been evaluated and compared to a baseline configuration (Tesla) in a study by Annapragada et al. [47]. The starting configuration for a Battery Heat Acquisition Systems (BHAS) is the Tesla system approach as it is utilized to regulate thermal losses from a 53 $\mathrm{kW\,h}$ Li-ion battery module in the commercially available Tesla Roadster electric car [48]. The system circulates a series of parallel battery coolant channels around each Li-ion cell, effectively cooling the cylindrical cell's exterior. The 18650 A Li-ion batteries, with a predicted cell-level power density of 300 $\mathrm{W\,h\,kg^{-1}}$ and a estimated thermal load peak of 126 kW for the hybrid-propulsion system, were evaluated.

The heat transfer components of the six configurations presented in Fig. 3 are [47]:

(a) A conduction channel (in yellow) links the cells to a plate heat exchanger attached to the cells' edge, with coolant flowing vertically along the cells' height (out of the page);
(b) Heat pipes (in orange) are stacked between the battery cells and linked to a plate heat exchanger joined to their edges, with coolant running vertically across their height (out of the page);
(c) Coolant flows from left to right via heat pipes (in orange) stacked between cells and linked to a pin fin heat exchanger.
(d) Coolant flows from left to right via conduction routes coupled to a pin fin heat exchanger;
(e) Equally spaced batteries submerged in a phase change coolant; heat is removed by boiling the coolant FC-87;
(f) Batteries stacked between plate heat exchangers with an 8 mm channel height.

The heat exchanger to battery mass ratio, the temperature differential between the cell core and the fluid, and the pressure drop necessary to accomplish cooling are the parameters considered in the analysis. The heat transfer analysis showed that none of the configurations studied have a negative impact on the maximum temperature difference across the cell and that the majority of studies have better thermal performance and lower weight than the baseline design especially for cell thicknesses below 22 mm. The configurations that use a conduction pathway have the lowest weight ratios. Weight ratios are lowest in setups that employ a conduction route, but in contrast the pressure loss is greatest.

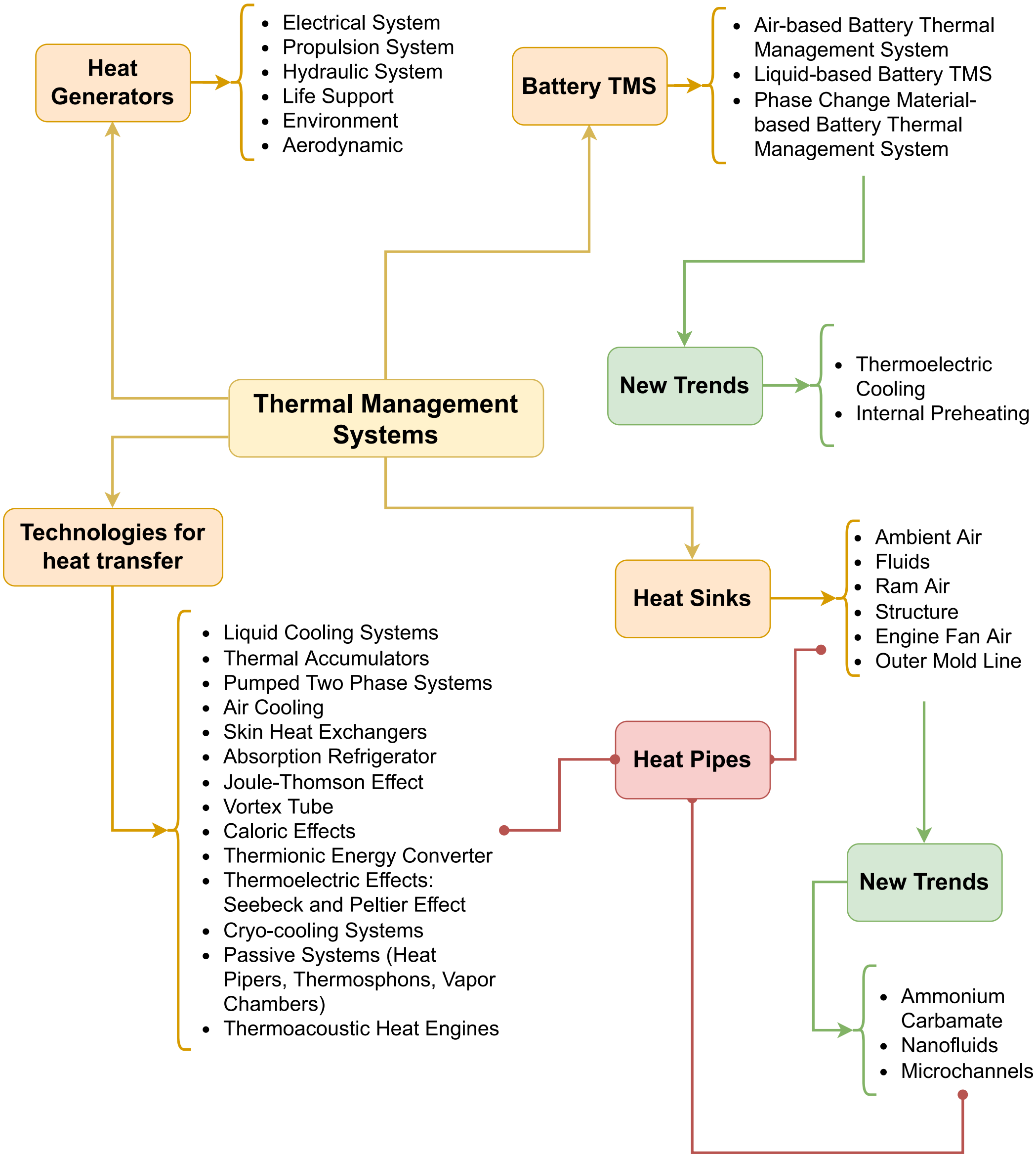

Fig. 1. Overview of the technologies for thermal management systems.

Heat pipes use copper instead of aluminum, so it adds weight to the design. However, heat pipes minimize the mass flow rate of coolant necessary to meet temperature limits, and when pressure drop is taken into account, heat pipe designs seem to be helpful within a limited range. Since the pressure drop for air is substantially greater than the pressure drop for liquids, one of the primary advantages of employing liquid as a coolant is the reduction in pressure drop. Thus, for thermal management setups employing heat pipes with plate heat exchangers or pin fin cooling, liquid cooling should be preferable to provide higher overall performance.

Regarding immersion cooling using FC-87, two concerns were raised: the first is the needed superheat temperature differential for pool boiling, and the second is the minimum distance between two adjacent surfaces to avoid vapor lock. Immersion cooling would not work for an aircraft BHAS because of these two reasons.

Kellermann et al. [49] designed and optimized new BTMS for a 19-seat hybrid electric aircraft. It has an all-electric design mission and uses a combustion engine for range extension. The authors proposed a ThermoElectric Module (TEM) as a cooler of the BTMS. In Fig. 4 it is possible to see the sketch of the proposed BTMS. The Heat Acquisition System (HAS) is attached to the cold side and the Heat Sink System (HSS) to the hot side. The former is responsible for collecting heat, while the latter is in charge of rejecting it to the ambient. Heat pipes are assumed for the HAS. A finned ram air Heat Exchanger Model (HEX) with rectangular channels is developed for the HSS.

The results demonstrated that the BTMS proposed for the most adverse combination of the three parameters (International Standard Atmosphere (ISA) temperature + 35 K; battery operating temperature = 295 K; and battery discharge efficiency = 0.90), resulted in a 16% increase in aircraft Maximum Take-Off Mass (MTOM) whereas the most advantageous combination (ISA temperature + 15 K; battery operating temperature = 325 K; and battery discharge efficiency = 0.95) only caused a 2% increase in MTOM.

Jang et al. [50] performed a study where the thermal performance of a liquid cooling system combined with heat pipes for Li-ion batteries under operating conditions was analyzed. They developed a transient thermo-fluid simulation model that allowed to analyze performance characteristics of three different BTMs: (a) Liquid Cooling (LC); (b) Liquid Cooling with A-type heat pipe (LCA); and (c) Liquid Cooling with B-type heat pipe (LCB). These different BTMs are depicted in Fig. 5.

The results of simulation indicated that, LCB shows much better performance than the LC, owing to the increased heat transfer area. The

Table 1
Heat transfer technologies in decreasing order of Technology Readiness Level (TRL).

Heat transfer technology	Description	Challenges and opportunities
Liquid cooling systems	Most often used cooling method in electric vehicles along with air cooling. On-board coolants, engine oil and fuel, can be used for cooling. Water is another form of coolant that has good thermophysical and thermodynamic properties [25]. Direct and indirect cooling are the two methods of liquid cooling that may be used to extract heat from a heat source. Direct liquid cooling relies on direct contact between the coolant and the component surface. Indirect liquid cooling relies on a coolant running via tubes to remove heat, like in the case of a cold plate design.	Water specific heat coefficient in $\mathrm{J\,kg^{-1}\,K^{-1}}$ is around four times that of air, so liquid cooling, on the one hand, allows for more heat collection while being more compact [25]. The TRL for this technology is high (>7) [20] since it has been incorporated to previous aircraft. On the other hand oils have an advantage against water because their boiling temperature is more than 100 degrees Celsius [26].
Air cooling systems	Uses an air cycle to transfer the heat. A source of hot air can be taken of a bleed in the engine and a source of cold air could be taken of the outside of the aircraft (ram air).	The air-cooling system is less effective during ground operations, take-off, go-around, and other periods of high power, low-airspeed operation [16]. Conversely, high-speed descents provide excess air and can cool the engine, subjecting it to abrupt temperature fluctuations. The TRL for air cooling systems is high (>7) [20].
Skin heat exchangers	Skin heat exchangers have a cold side that is ambient atmospheric air and a hot side that is a fluid that transports waste heat away from aircraft heat sources [16]. Although the heat transfer surface is built into the airframe, cooling may be improved using fins or other methods. It can be classified into two types: air/air type and air/liquid type.	Great solution for TMS but can bring structural integration problems and negative effects on drag and weight [27]. The TRL is high since it has been used in other aircraft (>7) [20].
Passive systems	Heat pipes, thermosyphons, and vapor chambers are examples of passive heat transfer components. Heat pipes are closed loop, sealed systems having a porous wick saturated with a working fluid and a hollow center in the pipe element. In this systems, the fluid vaporizes when heat is absorbed at one end of the pipe, and the vapor travels to and down the hollow center part of the pipe. Then, the vapor condenses at the chilly end, and the liquid returns to the wick. The difference between thermosyphons and heat pipes is that these devices use gravity and natural convection to force the working fluid to flow. Other uses, on the other hand, should be investigated. Heat transmission in two or three dimensions is possible using vapor chambers, which are analogous to heat pipes [28].	The passive transport components offer several benefits, including the lack of moving components, inexpensive maintenance, and the absence of any input energy. They are adequate for “federalized”, local cooling applications and they can be used in different cooling systems. Heat pipes have been used in aviation systems for avionics cooling, electromechanical actuator cooling, and anti-/de-icing systems [29–31]. Some of the constraints of heat pipe design are the performance dependency on gravity orientation and on short transit lengths (3 m) [16]. Thermosyphons, like heat pipes, appear to be particularly well suited for cooling electrical devices in aeronautical applications. Indeed, there is a lot of potential for incorporating them into larger aircraft thermal management systems. The TRL of these passive transport components in aircraft is high (>7) since it has already been employed [16].
Pump two phase systems	The hybrid two-phase cooling loop system consists of an evaporator, mechanical pump, reservoir/condenser, connecting pipes, etc. Under the influence of the capillary force, the liquid flowing into the evaporator enters the cavity of the lower evaporator, absorbs the heat, and experiences a phase change to remove heat from the steam chamber. Under the operation of the cooling system, it flows from the steam pipe into the reservoir and releases the heat to create a liquid [32].	Traditional air cooling and single-phase liquid cooling (water cooling) are insufficient to meet future requirements. The two phased cooling loop system offers high temperature control accuracy, a long heat transfer distance, a high heat dissipation capacity, and a high stability capacity, allowing it to satisfy future heat dissipation needs [33]. The TRL for this technology is (>7) because it is being used in some aircraft [20].
Phase Change Material (PCM) for batteries	These materials have the property to release or absorb energy at the transition phase providing, respectively, heat or cooling. PCMs have high fusion temperatures, so they can absorb a great amount of heat without causing substantial changes in temperature and volume and because of that they function as a thermal storage device (useful for occasional peak loads) [16].	The use of PCM TRL between 4 to 6 [20] - for passive cooling is easy and does not necessary need the use of additional power components such as a fan/blower, pump, pipelines, or chiller. By absorbing and storing heat during phase transition, it provides rapid temperature responsiveness, effective suppression of temperature upsurge, and temperature homogeneity The PCM-based Battery Thermal System is efficient, inexpensive, and simple to maintain. Low thermal efficiency, the growth of volume and liquid leaking after melting might potentially be a problem [34].
Absorption refrigerator	Absorption refrigeration is a technique that drives the cooling cycle using low-quality heat (such as hot water or low-pressure exhaust gas in the case of a gas turbine) rather than electricity. It is like the standard vapor-compression refrigerator, but the compressor unit is replaced by the absorption unit [35].	Although it does not cool as efficiently as systems with compressors, these devices are silent, have no moving mechanical components, and require less energy (thus, less power consumption). TRL for this technology is 4–5 in the aerospace field [20].
Thermoelectric effects	These are devices that create electricity from heat, through the “Seebeck”effect, or absorb heat, via the “Peltier”effect, when a voltage is applied to them [16].	These materials’ efficiencies are improving, and different types of installation architectures may improve power density to the point where they become more appealing for larger-scale use. Putting thermoelectric generators between a gas turbine engine’s hot core stream and cool bypass flow, may allow for a realistic design range to be established, with a positive influence on aircraft specific fuel consumption [36]. The TRL for thermoelectric heat sink in aircraft has been set between 3–4 [20].

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authors calculated that in LCB the maximum temperature of the battery pack decreases by 6.1 °C and 9.4 °C under the basic and optimized conditions relative to those in the LC, respectively.

More recently, Zhang et al. [51] proposed a novel battery thermal management system that combined liquid cooling channels and phase change materials. Firstly, the authors studied the effect of the combination of different PCMs on the heat dissipation performance and introduced a liquid cooling channel to reduce the temperature of the battery pack. In order to increase the heat dissipation of the battery

Table 1 (*continued*).

Vortex tube	Vortex tube is a refrigeration device with no moving parts that separates cold and hot streams. This device can turn high-pressure gas into two different flows with two different temperatures [37].	The main drawback of this technology is the lower lifetime of the materials used. Consequently, the maintenance costs are higher. Many studies were made in order to decrease it. New vortex tubes made of aluminum had better performance when combined with new angles of the valves. This development must continue so the maintenance costs will decrease and the efficiency will increase as desired [37]. TRL <3.
Thermionic energy converter	Thermionic energy conversion is a heat engine that directly converts heat into electricity. The energy source is heat and the electron is the working fluid. One surface is heated in order to become an emitter and other surface is cold enough to become a collector. This phenomenon produces an electromotive force between two electrodes [38]. These two surfaces are separated by a plasma or vacuum.	Researchers consider this technology as an energy converter with huge potential. Nonetheless, the development of vacuum Thermionic energy converters has been affected by their low work function. Making Thermionic energy converters capable to replace the current energy production systems is the main goal of the scientists of nowadays [38]. The future of this technology passes through this development. TRL <3.
Joule-Thomson effect	Joule-Thomson effect is an isenthalpic phenomenon used in liquefying gases. The highly compressed gases when suddenly allowed to expand create the desired cooling effect without production of work or transfer of heat. With the pressure reduction, the temperature decreases in under certain conditions [39].	Joule-Thomson (JT) cryocooler requires higher performance, reliability and robustness in the design and operation. A considerable amount of work has been made in order to develop this technology so it could be able to replace the cryogen of liquid helium in the industry [39]. The TRL of this technology is between 1–3.
Caloric materials	Caloric materials consist, mainly, in three possible effects: magnetocaloric (MC), electrocaloric (EC) or mechanocaloric (mC). These materials generate cooling effects by the influence of magnetic, electric, or mechanical forces. Caloric materials show reversible thermal changes that are parameterized via adiabatic temperature change ΔT [40].	Worldwide scientific community sees caloric materials as a great potential and as environmental-friendly cooling technology that can be incorporated in both micro and macro devices. The main challenge scientists face in developing caloric materials is to increase the adiabatic temperature change and the isothermal heat with greater resistance and efficiency [40]. With all the studies around this technology, it is expected in the future the engineers will be able to prototype heat pumps based on all three caloric effects. The TRL for the caloric materials has been estimated between 2–3 [41].
Cryo-cooling systems	In order to cool the heat load, cryo refrigeration systems are used. This system consists of the boiling or sublimation of the solid cryogens of fluid in low temperatures [42]. This technology can provide temperature stability with insignificant power requirements.	Cryogenic systems that use a reverse-Brayton cycle cryocooler (RBCC) are the most common solutions [43]. Cryo-cooling can enhance engine efficiency and almost do not have moving parts (more reliability). However, they add weight to the system [43]. The TRL is low (1–3) [20].
Thermoacoustic heat engines	Thermoacoustic heat engines convert heat in acoustic power. This technology is composed by a resonator filled with working gas, two heat exchangers and a stack in the middle of them [44].	Thermoacoustic heat engines are consided by many engineers as one of the most efficient energy sources for the future. This technology can operate with a small amount of electrical energy, but the thickness of hot heat exchangers is the main challenge that the scientists are trying to overcome. It affects the maximum acoustic power generated and the maximum pressure amplitude. With the reduction of the thickness of the hot heat exchangers, it is estimated that the maximum acoustic power generated will increase around 3% [44]. The TRL of this technology is between 1–3.

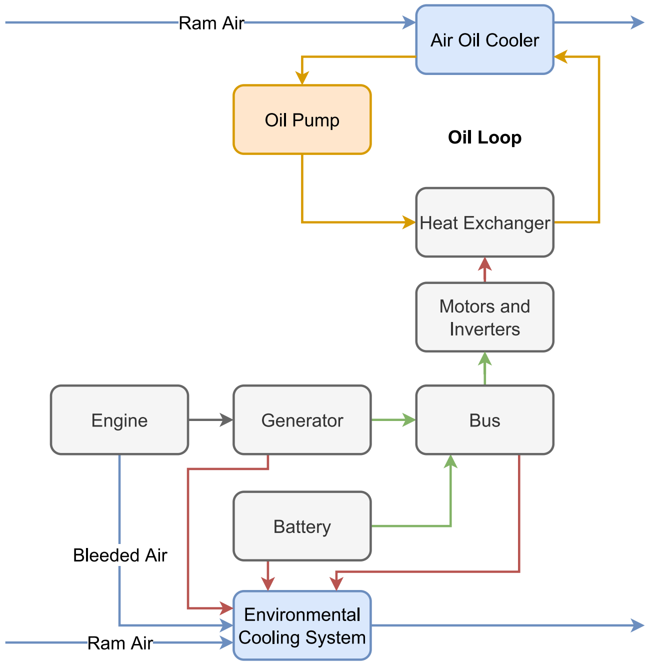

Fig. 2. Environmental cooling system modeled in Numerical propulsion System Simulation (NPSS), adapted from [46]. The chosen color scheme for the arrows is the following: blue denotes air; dark yellow stands for oil; red represents waste heat load; green corresponds to an electric connection; and gray is a mechanical connection.

without energy consumption, they proposed a new method of adding fins on liquid cooling channels.

In Fig. 6 it is possible to see the 3D model of the BTMS where combined fins on and between liquid cooling channels in PCMs are visible. Due to the relatively high temperature of the middle battery cells, Zhang et al. [51] used 2 different types of PCMs: one (Fig. 6a) filled around the middle cells; and another (Fig. 6b) around the peripherical battery cells. In the first type (Fig. 6a) the PCM used was expanded graphite and in second type (Fig. 6b) the PCM used was paraffin wax.

In this study, it was concluded that the combination of PCMs could significantly reduce the maximum temperature of the battery pack; with the introduction of the liquid cooling, the maximum temperature of the battery pack could be effectively reduced, but the temperature difference was slightly increased and reasonable arrangement of fins on and between the liquid cooling channels reduced the maximum temperature and improved the temperature uniformity of the battery pack.

Yetik et al. [52] did research with the goal of understanding the effect of different variables when cooling with forced convection a hybrid electric aircraft battery, considering its busbars (highlighted previously as an important aspect [53]), using a fluid with nanoparticles (liquid cooling). The motivation behind their work was the need to improve the thermal conductivity of the coolant and consequently to optimize the heat transfer dissipation by forced convection in batteries. They focused on specialized nanofluids which has been shown to improve cooling effectiveness in the literature [54]. To investigate this, the study used the nanoparticle Fe_2O_3 and different combinations of base fluids, volumetric fractions, discharge rates and inlet temperatures and velocities of the coolant. Simulation results revealed that the nanofluid-based

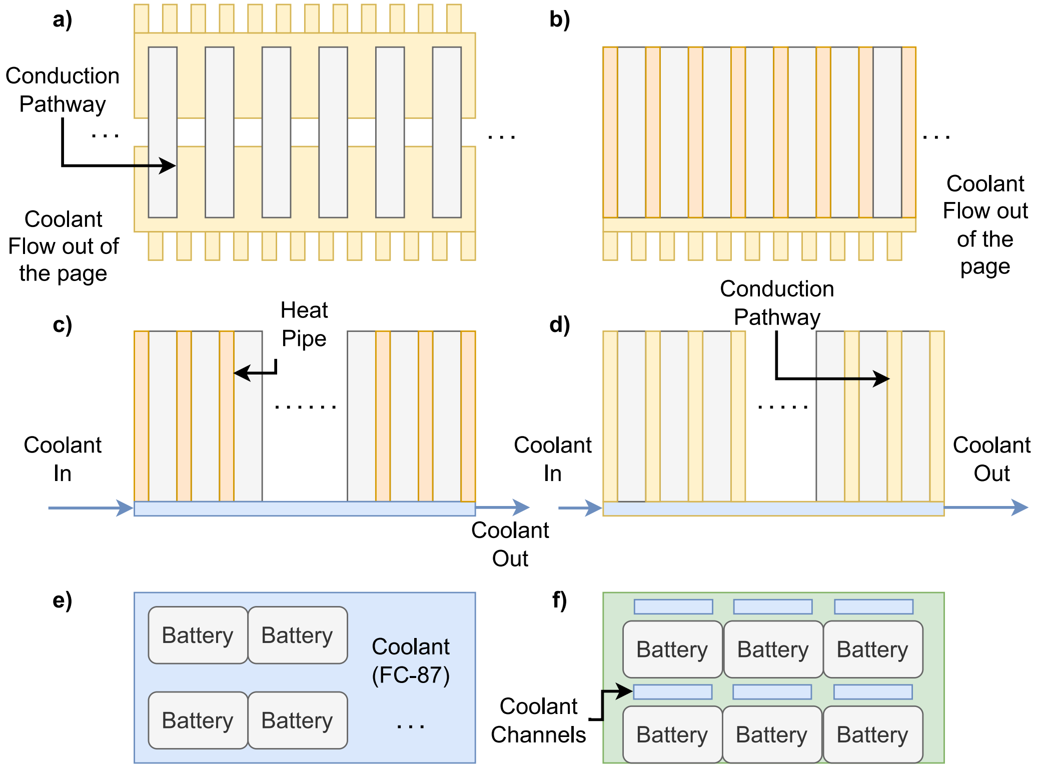

Fig. 3. Thermal management configurations analyzed in [47] (adapted).

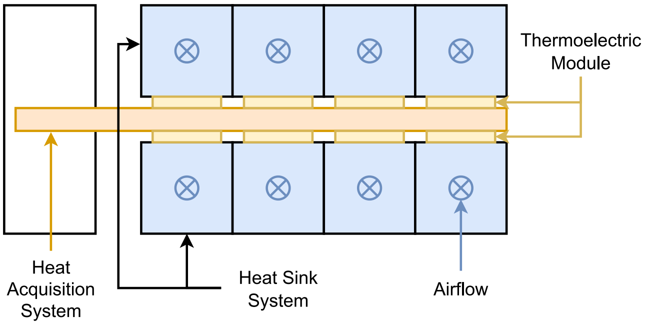

Fig. 4. Sketch of the BTMS proposed by Kellermann et al..
Source: Adapted from [49].

coolant could maintain the battery's temperature at an appropriate level. At the end, water was identified as the best fluid coolant (higher thermal conductivity). Another observation from this study was that increasing the mixing ratios and inlet velocities has the beneficial effect of decreasing the temperature of the battery.

In the context of the next-generation of the batteries, Yue et al. [17] reports emerging technologies for BTMS. One of these technologies uses **internal preheating** to improve the battery performance and reduce the waiting time to warm up the batteries for low ambient temperatures. This is done by means of a metal foil inserted into the battery that acts as heating source at low temperatures. With this foil the battery cell can be heated from −20 °C to 0 °C in 20 s spending 3.8% of its capacity.

3.2. Electrical machines

Electrical machines, namely motors, generators, inverters, and converters, for hybrid-electric aircraft will have to be megawatt-class, and although most of them have great efficiency rates, significant amount of heat will have to be removed (order of kW). Rheaume et al. [56], executed a study based on a TMS of a parallel Hybrid-Electric Propulsion (HEP) system of a commercial single aisle aircraft. Considering efficiency increases of 1% for Batteries and 2% for Motor Drive with respect to the baseline, expected in 2030, the impact on TMS weight was investigated [57]: the heat load decreases and consequently the Batteries Ram Coolant Cooler (RCC) weight reduces 26% and the Motor Drive RCC weight reduces 38%. This new scenario leads current studies to look at the future TMS with more attention and detail.

Schiltgen et al. [58] developed a TMS architecture for a concept aircraft, the Environmentally Conscious (ECO-150R). The ECO-150R is a 150-passenger (PAX) airliner concept characterized by a turboelectric distributed propulsion. Given the power levels involved in the ECO-150R, the electrical components are estimated to produce nearly 1491 kW of heat at the top of climb flight condition. The TMS to manage that heat consists of a recirculating liquid cooling system with ducted radiators (ram air heat exchangers), as it can be seen in Fig. 7. The analysis and design of the TMS architecture was done by using the PANTHER software [58].

Water was used as the coolant and collects heat from the motors, generators, controllers and power cable. The heat is rejected on the radiator to ram air in a duct. This latter component is specially designed to make use of the Meredith effect [59] to simultaneously increase heat rejection capacity and reduce cooling drag. The TMS includes two ducted radiators (tube-and-fin ducted configuration), two pumps and a simple network of coolant piping.

Chapman et al. [55] executed a study of the TMS architectures for three different aircraft concepts: the turbo-electric tiltwing Vertical Take-Off and Landing (VTOL) developed within the Revolutionary Vertical Lift Technology (RVLT) project, the Single-aisle Turboelectric AiRCraft with Aft Boundary Layer ingestion (STARC-ABL) and the Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS). They performed a comparison between the baseline configuration and advance configuration. The baseline configuration represents state of the art technology and relies on a DC electric bus.

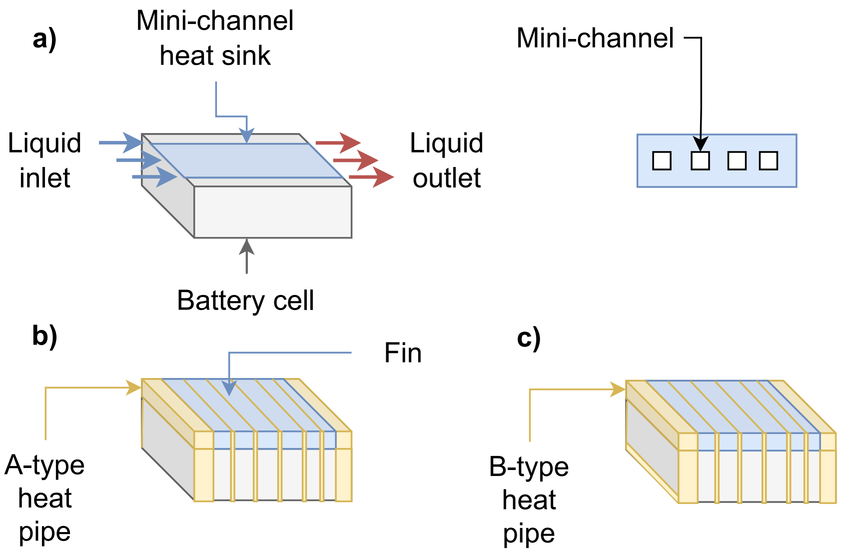

Fig. 5. Schematics of battery thermal management systems (BTMSs).
Source: Adapted from [50].

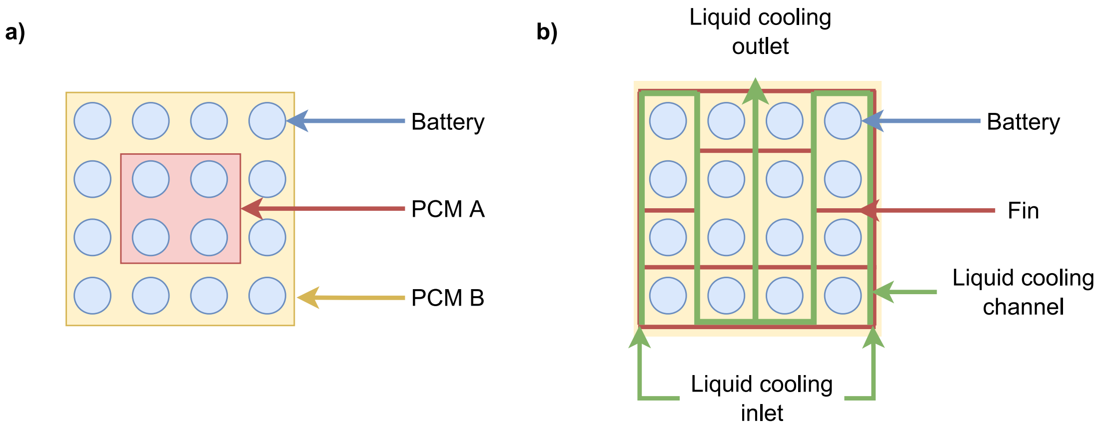

Fig. 6. (a) BTMS with two PCMs and (b) BTMS with liquid cooling channel and fin.
Source: Adapted from [51].

Table 2
Aircraft specifications, adapted from [55]. The following nomenclature is adopted for this table: R represents range; cruise altitude and Mach number are denoted by h_{cr} and M_{cr}, respectively; number of passengers is PAX; EdM, CdE and ICE stand for electrically-driven motors, combustion-driven engines and internal combustion engines, respectively; CTOL corresponds to conventional take-off and landing; and TOGW is the take-off gross weight.

Concept	Type	R (nm)	h_{cr} (ft)	M_{cr} (–)	PAX	EdM	CdE	ICE	Battery	TOGW (lb)
STARC-ABL	CTOL	3500	35,000	0.7	154	1	2	2	No	133,370
RVLT Tiltwing	VTOL	400	10,000	0.3	15	4	0	1	Yes	13,866
PEGASUS (all-electric)	CTOL	200	20,000	0.48	48	5	0	2	Yes	53,041

The advance Electrified Aircraft Propulsion (EAP) power system is based on three major technological advancements: the High Efficiency Megawatt Motor (HEMM), a low weight and efficient electronical transmission scheme, and high efficiency converters. The HEMM utilizes a superconducting rotor coil and cryogenic cooling to increase motor efficiency. In the STARC-ABL and RVLT tiltwing aircraft the power is taken from a gas turbine driven generator that produces AC power. In the PEGASUS, DC power is directly obtained from the battery. In Table 2, a brief characterization of the aircraft explored in that paper is given. Chapman et al. [55] implemented the models in Python and embedded them in the OpenMDAO framework. As optimization solver, the Sparse Nonlinear OPTimizer (SNOPT) was used.

The baseline TMS for the STARC-ABL was divided into an engine oil loop, a rectifier loop and the tail mounted boundary-layer ingesting (BLI) fan loop. The baseline generator was added to the engine oil cooling loop, which uses engine bypass air to reject the heat to the environment and utilizes a fuel-to-oil cooler (FOC). The propylene glycol 30% (PGW30) coolant was considered for a cooling loop for generator's rectifier and controls, and for another cooling loop to motor and inverter of the BLI fan. The fan air was only considered for cooling engine loop (Fig. 8).

The advance TMS architecture is also simple with the removal of oil cooling loop and replacement of the rectifier load with generator load and the air-cooling loop for the engine (Fig. 9).

The results of the simulations can be seen in Table 3. In addition to simulating baseline TMS and advance TMS, they did a Corrected Baseline where they only included the electric system. The coolant fluid was updated from PGW30 to PSF-5 (coolant specific heat is reduced)

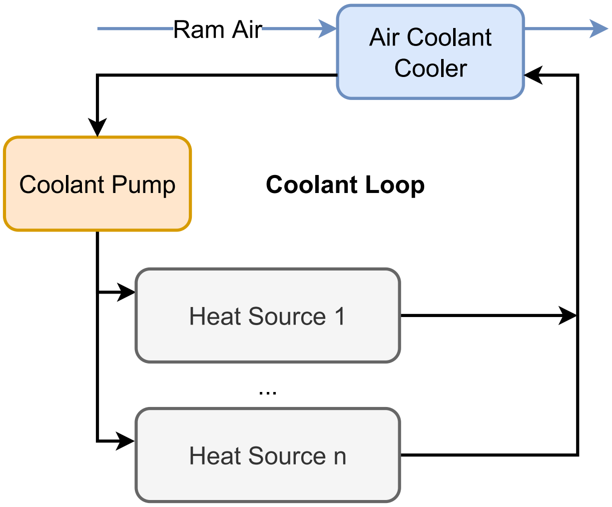

Fig. 7. Thermal management system diagram.
Source: Adapted from [58].

Table 3
STARC-ABL TMS design metrics [55].

Total TMS loop	Baseline	Corrected baseline	Advanced
Weight (kg)	197.97	109.33	50.77
Power required (kW)	0.20	0.14	0.31
Drag (lbf)	14.68	13.11	4.52

in the advance configuration which causes an increase of the required power due to higher viscosity of PSF-5 [55]. Although the advance TMS requires more power to run than the baseline one, both weight and drag are one order of magnitude lower.

Schnulo et al. [12] also proposed other TMS for the STARC-ABL, using a passive Outer Mold Line (OML) Cooling. In this model, the power system remains the same as described in [55]. The concept of OML cooling is to employ the aircraft's exterior mold line as a heat sink, transforming the skin into a multi-functional structure that improves aircraft performance. The power consumption to run the system will be reduced since the pump consumption decreases and the drag penalty will be minimized by eliminating the requirement for ram air to extract energy from the heat exchangers. To perform an OML cooling, two methods can be used: active and passive cooling. The first one consists in actively cooling the exterior mold line by injecting coolant through flat metal tubes embedded into the skin. In the second and favored one, the heat is transferred to OML using wicked heat pipes and then is dispersed throughout the OML panels in order to be rejected using Oscillating Heat Pipes (OHP). The passive cooling of the OML results in a weight penalty for the airplane but no additional power is required, and no drag is created. Assuming the passive OML cooling, a Computational Fluid Dynamics (CFD) analysis was carried to estimate the convective heat transfer coefficient to determine how much heat may be rejected through the OML, to compare both baseline and advanced configurations of the STARC-ABL TMS. According to the findings of this study, the OML cooling system is 112% heavier than the baseline STARC-ABL TMS power system, but it has no power or drag penalty for the airplane and saves 0.8% more fuel than the advanced cooling model.

The TMS architecture for Revolutionary Vertical Lift Technology (RVLT) concept consists in two main types of cooling loops (Fig. 10). The first type, uses PGW30 as coolant, gathers heat from the loads and rejects them using an air-to-coolant heat exchanger. The motors are cooled in series with the power electronics to reduce complexity. The second type is an oil cooling loop, like the STARC-ABL, to cool the engine (engine gearbox, accessories, and bearings).

Table 4
Tiltwing TMS design metrics [55].

Total TMS loop	Baseline	Corrected baseline	Advanced
Weight (kg)	54.04	46.7	26.94
Power required (kW)	10.54	9.31	3.81
Drag (lbf)	−39.92	−35.21	−13.89

Table 5
PEGASUS TMS design metrics [55].

Total TMS loop	Baseline	Advanced
Weight (kg)	195.55	138.89
Power required (kW)	0.22	0.30
Drag (lbf)	17.64	12.67

The advanced TMS architecture for RVLT concept is one engine coolant loop and motor coolant loop (Fig. 11). Each loop utilizes the PSF-5 as cooling fluid. Architectures for the power electronics and motors are identical to those found within the baseline version. Cooling for the advance technology generator has been removed from the oil loop due to the reduced temperature limits associated with the HEMM and placed on a separate cooling loop.

The results are shown in the Table 4, where the use of puller fans causes the required power levels to be in the kW range for each of the baseline loops and net thrust is being generated (negative drag). Comparing the correct baseline with advance designs, the system weight is reduced by roughly 50%. The required power and net thrust are reduced by 60%. The motor loop weight decreases by 35% while the engine coolant loop by 20%.

In the case of the Pegasus, the baseline and advanced EAP architecture are the same since the battery will be producing DC power directly. The TMS architecture is modularized with loops consisting of an inverter and motor for the tip, inboard and BLI components with the battery split off on a second loop type (Fig. 12). In the baseline configuration, all loops utilize PGW30, but in the advance configuration, the tip, inboard and BLI loops utilize PSF-5 coolant. In both configurations, the battery cooling loops use PGW30 coolant.

The results are presented in Table 5 where a reduction of 30% in weight is achieved when comparing the baseline and advance configurations. There is an increase in TMS required power due to the rise in viscosity associated with the coolant used in the advance configuration but all power levels were significantly less than 1 kW. The reduction in drag corresponds to the lower power rejection requirements for the advance configuration.

Kellermann et al. [11] performed a study of different TMS architectures for a 180-passenger short range partial-turboelectric aircraft. They determined, using numerical optimization, the ram air based TMS that allowed minimum fuel burn. For the ram air-based TMS a centralized parallel TMS was implemented; this means that all electric components have being cooled in parallel. The TMS architecture (Fig. 13) consisting of cold plates for heat acquisition, pipes and pumps for hot-side heat transfer, two-pass cross-flow plate-fin heat exchanger for heat rejection, and a diffuser and a nozzle for cold-side flow velocity control.

In this study, the authors concluded that increasing electric components junction temperature to about 400 K could eliminate parasitic drag from the TMS in cruise entirely. For a realistic temperature of 380 K, there is an increase of 0.19% of fuel burn for an aircraft with 30% power split. In hot-day take-off conditions, the system needed a small puller fan installed behind the main heat exchanger. Alternatively, oversizing the TMS removed the need for a puller fan but increased additional fuel burn to 0.29%.

Chapman et al. [60] developed an integrated TMS for a six-passenger parallel hybrid quadrotor. It was based on a liquid based TMS strategy where a liquid coolant gathers the heat loads then rejects that heat to air through a liquid to air heat exchanger. The system

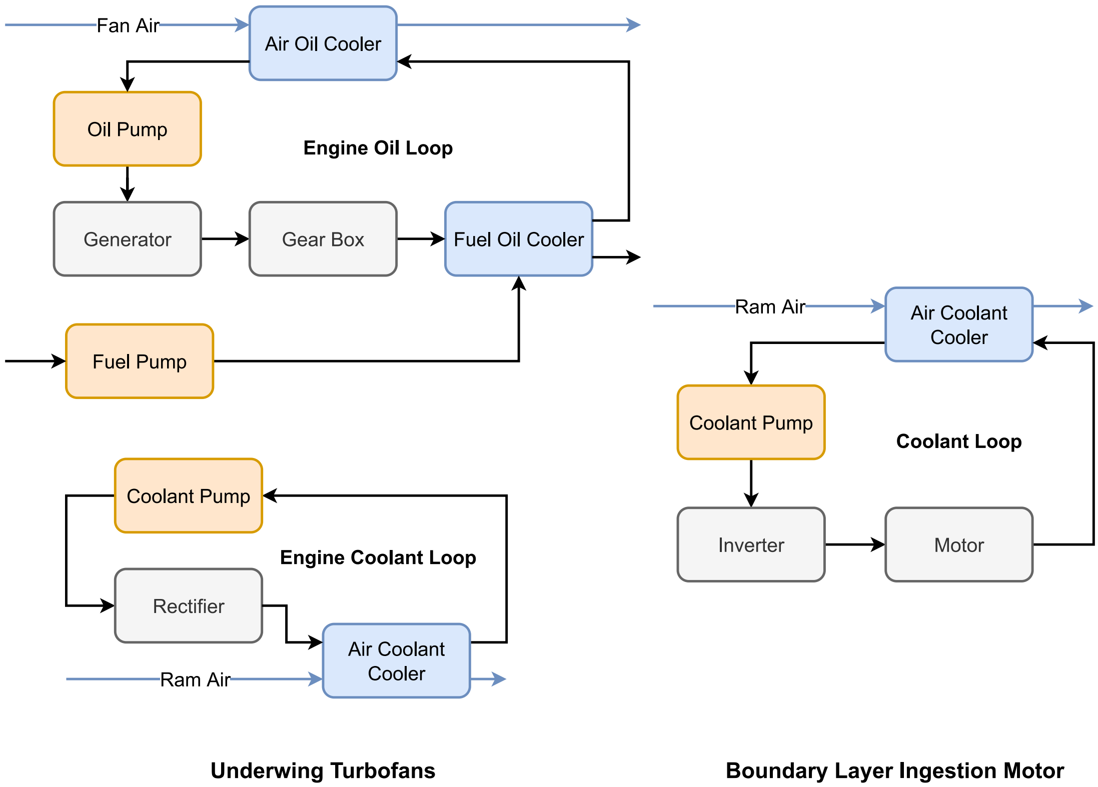

Fig. 8. STARC-ABL baseline TMS architecture.
Source: Adapted from [55].

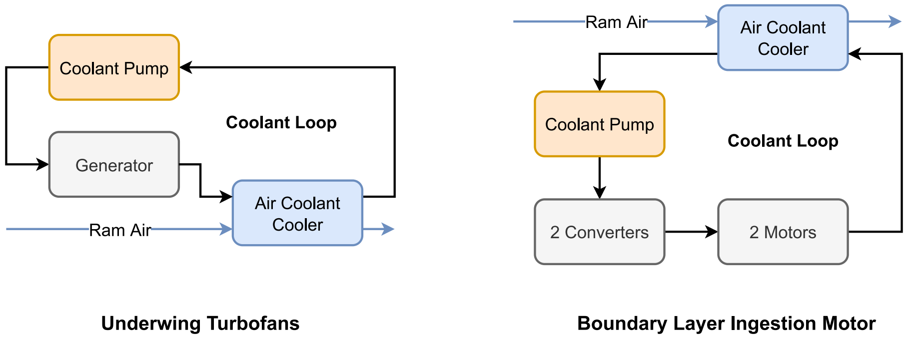

Fig. 9. STARC-ABL advanced technology TMS architecture.
Source: Adapted from [55].

components include heat exchangers, coolant tubing, pumps, ducting, puller fans and air network exhaust nozzles.

Two different TMS architectures are utilized in the system: an electric motor and driver cooling loop (for each motor) and a battery cooling loop, as it can be seen in Fig. 14. These TMS architectures were simulated in the Numerical Propulsion System Simulation (NPSS) code.

The authors concluded that the TMS architecture is a feasible option if coolant flow is kept constant and air flow is allowed to modulate naturally.

Shi et al. [61] presented a design of the thermal management system for a hybrid turboelectric regional jet and integrated it into the aircraft in the context of the NASA University Leadership Initiative (ULI) program. The architecture of the electric propulsion system used for this study is constituted by eight Integrated Motor Drives units (IMD) that are driven by two generators and one battery. The TMS presented in this study cools the electric propulsor, where the heating source includes the inverter and motor and the battery, using air from the Environmental Control System (ECS).

The architecture of IMD TMS studied by Shi et al. [61] is shown in Fig. 15. The oil selected for this oil cooling loop was Polyalphaolefin (PAO). The authors realized that this TMS architecture may not be able to remove all the heat generated from the inverter and the motor during take-off and climb, even if its capability satisfies the cooling requirements in other mission segments. The modeling and integration of TMS architecture was done in the Georgia Tech Hybrid Electric Analysis Tool (GT-HEAT) toolset.

To remove that peak thermal load during early mission segments they proposed and compared three different architectures: one with additional PAO for heat absorption, and two others with two types of PCM (magnesium chloride hexahydrate and Urea-KCL). The authors concluded that TMS with additional PAO has the largest penalties on weight and block fuel burn, while the corresponding penalties of TMS with PCM are much smaller, since the large latent heat of PCM makes it much lighter than PAO: comparing the two TMS with PCMs, the Urea-KCL presents smaller weight penalty because it has larger latent heat and thermal conductivity.

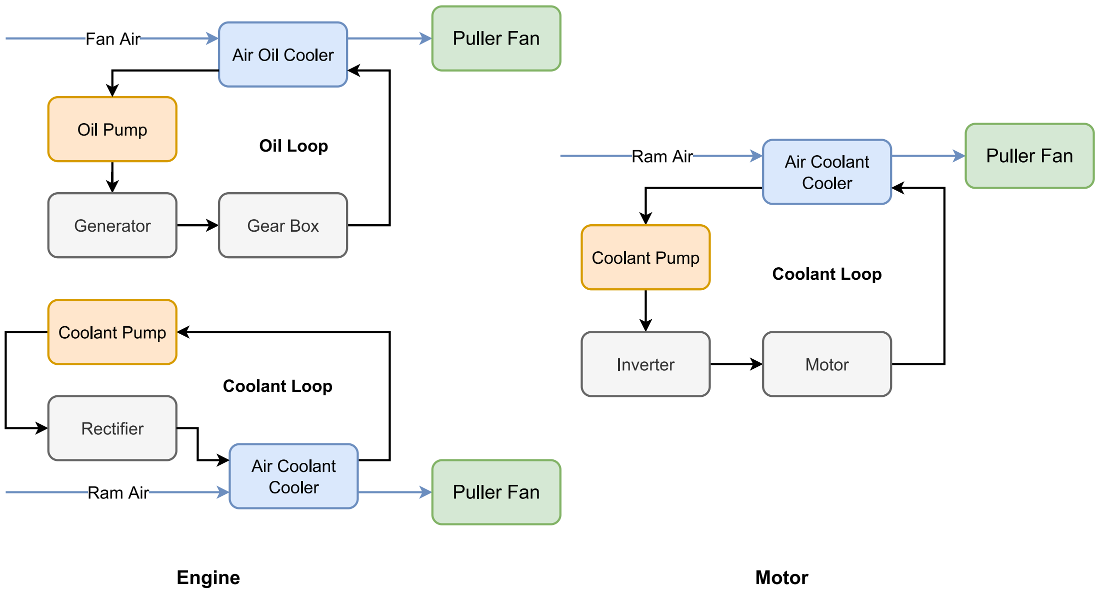

Fig. 10. RVLT tiltwing baseline TMS architecture.
Source: Adapted from [55].

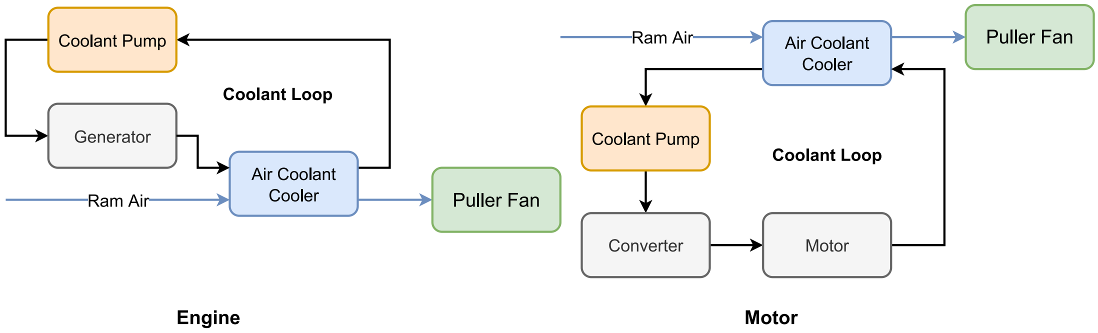

Fig. 11. RVLT tiltwing advanced technology TMS architecture.
Source: Adapted from [55].

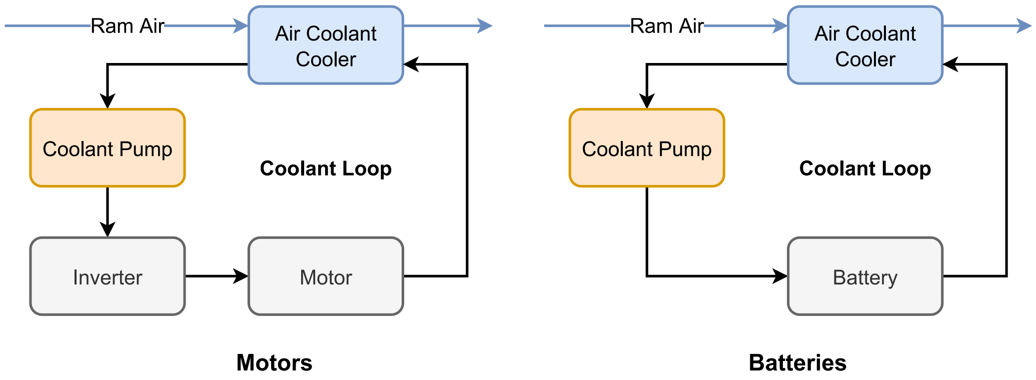

Fig. 12. PEGASUS TMS architecture for baseline and advanced TMS architectures.
Source: Adapted from [55].

Heersema et al. [62] proposed a TMS for Subsonic Single Aft eNgine (SUSAN) electrofan aircraft. SUSAN is a 180-passenger regional aircraft concept designed by NASA that uses 20 MW of power with waste heat in the order of 1 MW [62]. This initial value of the thermal management was provided by work done under CAS HEATheR activity for STARC-ABL concept by NASA. The main objective of this conceptual design is to reduce emissions by 50% while retaining the speed, size and range that is typical of large regional jets.

The temperature limits of most of the electric components require the waste heat to be rejected at relatively low temperatures between 30

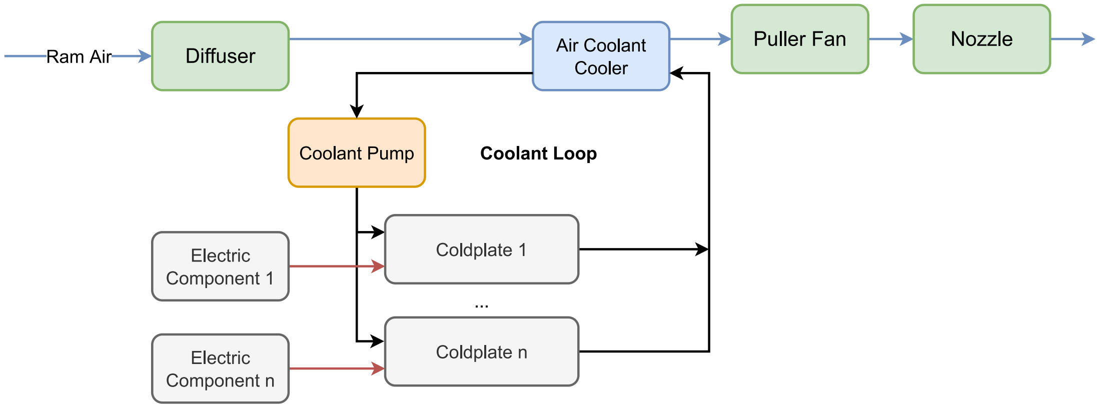

Fig. 13. Centralized parallel thermal management system (TMS).
Source: Adapted from [11].

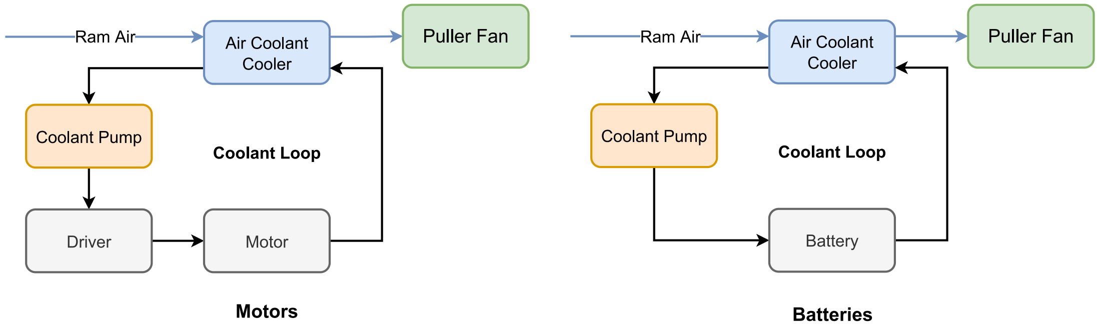

Fig. 14. Six passenger quadrotor TMS loop architectures.
Source: Adapted from [60].

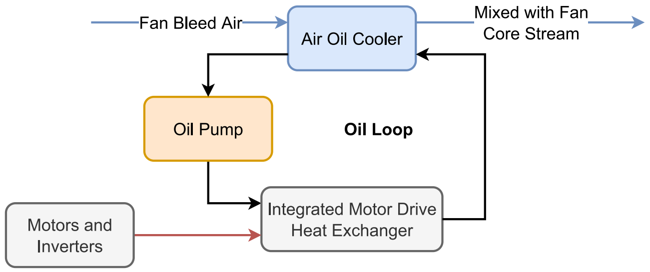

Fig. 15. Six passenger quadrotor TMS loop architectures.
Source: Adapted from [61].

and 200 °C. To manage the large amount of heat produced, Heersema et al. [62] planned three different thermal management loops that operate at temperatures appropriate for each thermal loads. The first thermal management loop will service the battery system and operates nominally at 40 °C, while the second thermal management loop will service the electrical system and operates nominally at 60 °C. The primary loads on the electrical systems loop are the electrical machines (motors and generators) and the converters, with a limit temperature of around 200 °C. The electrical thermal management loop will be connected to an OML surface heat exchanger as well as a liquid/air heat exchanger. The third thermal loop will service the turbofan and will be typical of a large, geared-turbofan cooling loop, operating at a nominal temperature between approximately 80 and 150 °C. The turbofan thermal loop will include an in-engine liquid/air heat exchanger and fuel/liquid heat exchanger.

Herber et al. [22] investigated the TMS design problem using a conceptual-level tool that enables the generation of novel architecture concepts through graph-based methods. The object of study was an UAV equipped with an Air Cycle Machine (ACM) based TMS. The architecture selection is done by a methodology that generates all possible graphs candidates under some general specifications. The ACM is composed by an ensemble of components, modeled using bond-graphs. These models are then combined such that the best architecture for the TMS of the UAV can be obtained. The process of graphs selection is described in Fig. 16.

The computing environment used for these studies was a single workstation with Matlab primary coding environment interacting with Open Modelica (component-oriented modeling software) to create, compile, and simulate the Modelica bond-graphs models [22]. At the end of the day, then have evaluated 32 612 TMS architecture graphs and a total of 63 437 successful simulations, to select the best configuration. A series of Pareto diagrams taking in consideration the target radar and flight control temperatures was presented. From the Pareto diagrams analyses 13 Pareto-optimal TMS architectures were obtained. The authors concluded that the work is only an initial filtering process to identify promising TMS architectures which should be investigated further under additional mission profiles and more thorough parametric design optimization.

Gkoutzamanis et al. [63] developed a study about TMS considerations for a hybrid electric commuter aircraft. The propulsive architecture, shown in Fig. 17, was based on one of the concepts presented in the European research project Hybrid ElectriC smAll commuteR aiRcraft conceptUal deSign (HECARRUS).

One of the objectives of this research was to answer the following research questions [63]:

1. what are the mission-based sensitivities (critical parameters) that are the major contributors in the TMS performance of a hybrid-electric commuter aircraft?

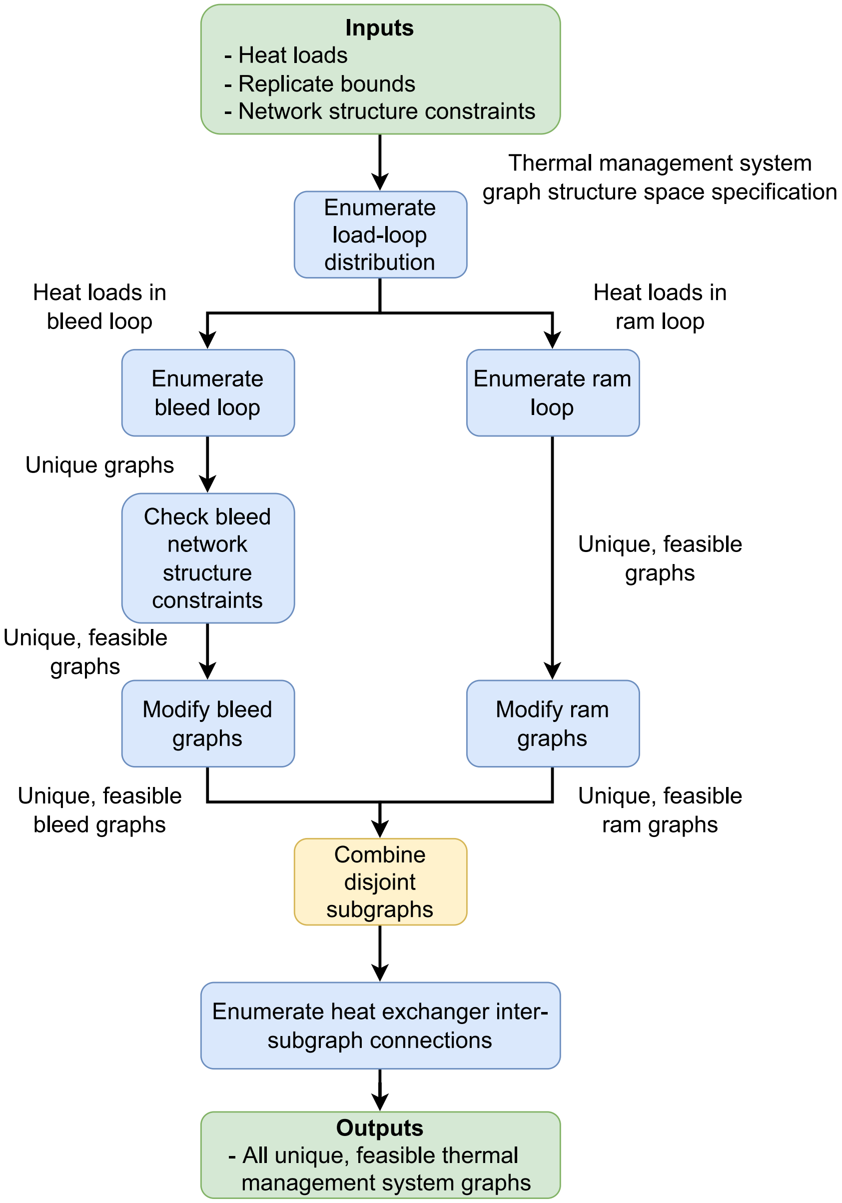

Fig. 16. Process for generating all aircraft TMS graphs (candidates architectures).
Source: Adapted from [22].

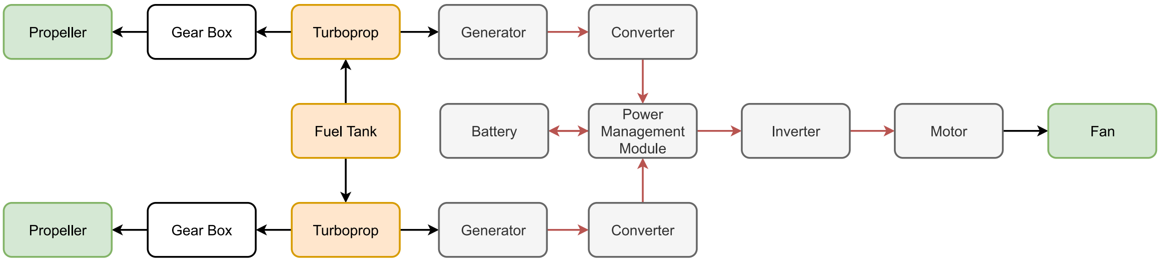

Fig. 17. Propulsive system.
Source: Adapted from [63].

2. what are the TMS design considerations in this aircraft if the Electric Propulsive System (EPS) must be thermally regulated to power an aft Boundary-Layer Ingestion (BLI) engine?
3. what is the weight of the studied TMS?

To answer the former questions, the authors developed an architecture for the TMS, admitting five scenarios for the power management strategy, (i) on ground at the airport, (ii) Take-off and climb, (iii) Cruise, (iv) Descent and (v) Landing. In the considered models the

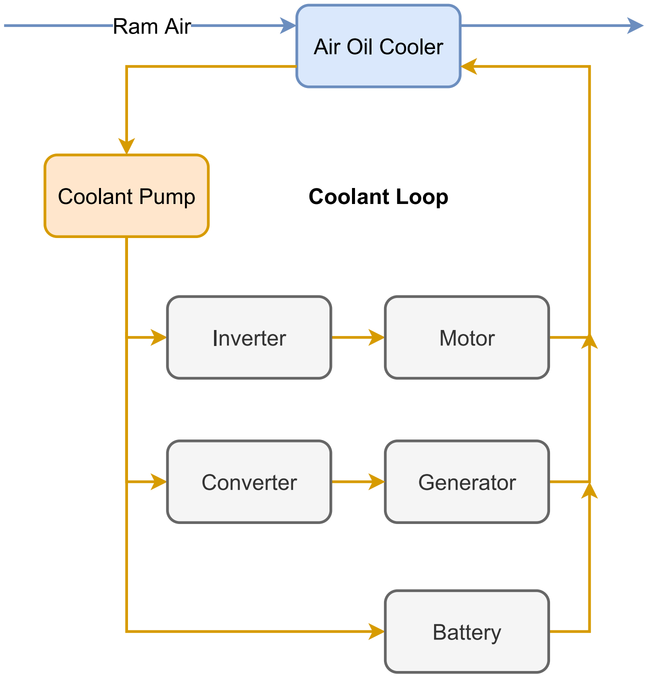

Fig. 18. TMS used in [63] (adapted).

initially size of TMS were defined under hot day conditions. For the simulations, the authors used an open-source software, based on Modelica and Python.

The TMS is based on two independent topologies selected for the aft BLI engine configuration: one is responsible for cooling the batteries, inverters and the generator coupled with the Gas Turbine (GT) engine; and the other is a serial cooling topology of the inverter and the electric motor used to power the aft BLI engine. After the two topologies absorb the heat loads, they proceed to the rejection of the heat at the air-to-liquid HEX [63]. A diagram of this architecture is presented in Fig. 18.

The conclusion presented by Gkoutzamanis et al. [63] start to answer the initial research questions. Regarding the first question, they concluded that the sizing of the TMS is a function of the selected propulsive configuration and the energy management throughout the mission. For the second question they observed that: a relatively small mass flow rate (about 0.2 $\mathrm{kg\,s^{-1}}$) allows for a laminar flow in the system with negligible pipe mass penalty; the positioning of the components directly affects the TMS; and the weight of the TMS increases with higher heat loads. For the last question they identified the Combined Specific Cooling (CSC) as a critical parameter to compare TMS of different configurations.

3.3. Combustion engines and fuel systems

A carbon free combustion (using hydrogen for example) may also be the future of Civil Aircraft, but it raises as well thermal management problems. Srinath et al. [64] proposed and assessed mainly three different thermal management system architectures for hydrogen-powered propulsion technologies towards a zero-carbon future. These designs were further developed and modified using hydrogen-powered fuel cells. The study covered the fuel system architecture to understand what the main challenges in the thermal management field were. The architecture of the fuel system for the utilization of Hydrogen included the fuel tank, low pressure and high-pressure pumps, heat exchanger (Fuel-Oil), fuel filters, fuel metering unit and flow meter and supply pipes delivering fuel to the Fuel Spray Nozzles (FSNs). Three different configurations for TMS were presented: TMS with exhaust gas heat exchanger in configuration 1; TMS with exhaust gas heat exchanger and compressor intercooling in configuration 2; TMS with exhaust gas heat exchanger, compressor intercooling, turbine air cooling heat exchanger, and flow expander in configuration 3. Exhaust gas-to-fuel heat exchangers use exhaust heat to raise fuel temperature while lowering exhaust gas temperature, and as a collateral result, lowering also exhaust noise. The addition of an intercooler between the compressor stages increases the useful work of the turbine because the total compressor work decreases. Incorporating a turbine cooling air HEX (hot air from the compressor used for turbine cooling is used to reject heat to the fuel) improves thrust for a specific combustor outlet temperature and it is also recommended to extend the life of the turbine components. Finally, upstream of the entrance of the FSNs or combustor, a flow turbine/expander could help reduce the excess pressure delivered by the pumps.

The integration of these components and the replacement of usual fuels by hydrogen bring several concerns. If there are any leaks, detecting and repairing them is difficult, and it may be necessary to replace the entire device; at the same time there is danger of hydrogen leaking into hot or fire zones during the replacement [64]. Manufacturing and maintenance of the components are both quite expensive and the increase of the required control system architecture for continuous monitoring and, if necessary, leak detection adds complexity to design and mainly increases the weight.

In a further analysis, the three architectures were updated in order to incorporate fuel cells. Fuel cells convert chemical energy from a fuel and an oxidizing agent (often oxygen) straight into electricity with a high efficiency. Solid Oxide Fuel Cells (SOFC) and Proton-Exchange Membrane Fuel Cells (PEMFC) are the most explored in the aviation industry. Cooling with cathode air, liquid cooling, cooling with separate air, cooling with heat spreaders, and evaporative cooling are some of the traditional cooling techniques studied by Aguiar et al. [65] and illustrated in Fig. 19.

Air cooling is one of the cooling strategy (for both PEMFC and SOFC), in which airflow via the cathode (or extra channels) offers adequate thermal regulation, although it may be ineffectual for local temperature control. Liquid cooling may be utilized instead of air cooling for systems with a power output larger than 2 kW. However, because of the extra cooling loops or heat exchangers, this approach is more costly than air cooling. Given its high thermal capacity, deionized water is often utilized. The latent heat owing to phase transition is used in evaporative cooling; consequently, the refrigerant flow is lower than in liquid cooling, resulting in a less costly and more compact system. The utilization of heat pipes incorporated into the structure is an alternative method for both PEMFC and SOFC. The heat is absorbed by the fluid within the pipe, which evaporates and is carried to the cold zone, where it condenses and releases heat to the environment.

Fig. 20 represents the engine fuel architectures assuming a total fuel cell powered system and devoicing a combustion system (fuel is delivered to fuel cells instead of the FSNs). The TMS and engine fuel system architecture with fuel cell is built using configuration 3 presented in Fig. 20, with exhaust gas heat exchanger, compressor intercooling, turbine air cooling heat exchanger, and flow expander. Depending on its power capacity, the fuel cell may be used to power one or more systems, including the fan or propeller, pumps, and gearbox, or the energy generated may be stored in a battery and then utilized as needed.

Jafari and Nikolaidis [67] also did a research on TMSs for Civil Aircraft Engines, where they reviewed the present and future challenges. The following topics summarize the most important concepts detailed in the paper:

1. Cooled Cooling Air (CCA) TMS to cool the compressor bleed air used for turbine cooling and performance improvement of the gas turbine engine.
2. Fuel-cooled system with two thermal management loops with various temperature levels to effectively handle all flight points.

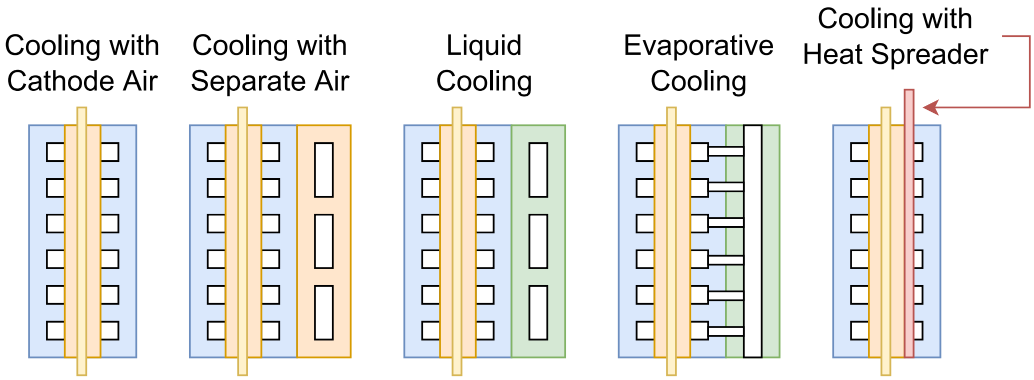

Fig. 19. Cooling methods commonly proposed in the literature for the fuel cells [65].
Source: Adapted from [64,66].

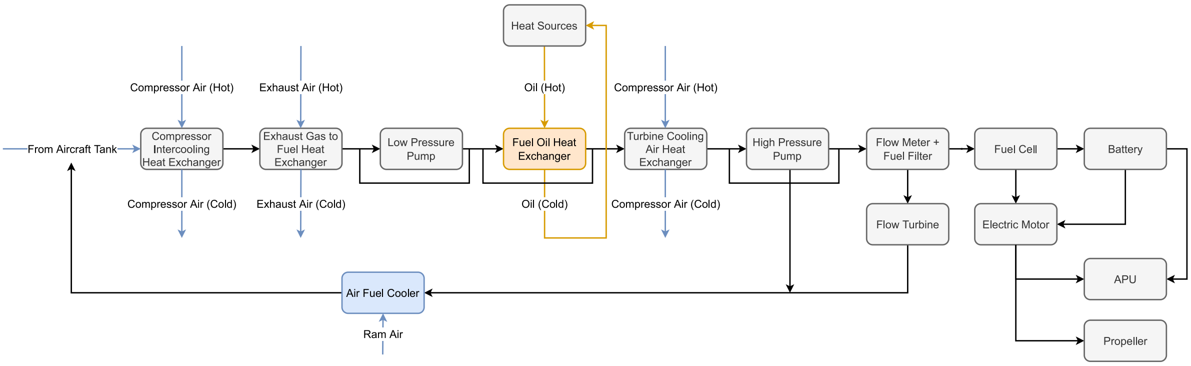

Fig. 20. TMS and engine fuel system architecture with fuel cell – Configuration 3 [64].

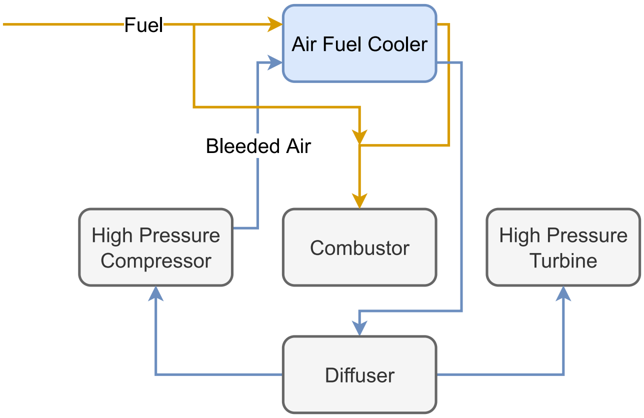

Fig. 21. Fuel-to-Air Heat Exchanger Concept.
Source: Adapted from [67].

3. Managing thermal loads in various parts of the gas turbine engine using various coolants (e.g., water, Therminol, and Thermally Neutral Heat Transfer Fluid (TNHTF)).

CCA using a Fuel-to-Air Heat Exchanger Concept was shown to be the most promising for increased engine performance. The use of a heat exchanger to cool compressor bleed air reduces the necessary air flow rate for turbine blade cooling, which is a major breakthrough. Fig. 21 depicts a diagram illustrating this concept. The primary disadvantages of this concept are its complexity and weight, as well as safety and reliability concerns.

The fundamental concept behind concept 2 is to have two cooling loops, each with a different temperature, to cope with varied degrees of heat flow throughout a flying operation. As a result, a thermal management system was proposed, as shown in Fig. 22, with an air-to-oil heat exchanger providing the first conditioned fluid, a second (fuel-to-oil) heat exchanger providing the second conditioned fluid, and a third air-to-oil heat exchanger in parallel flow communication with the second heat exchanger to meet the fluid temperature limits and providing the third conditioned fluid.

A different option is to absorb heat from engine fluids with a working fluid (e.g., water, Therminol, TNHTF, oil and fuel) [67]. Fig. 23 shows two schematics of this concept. In this implementation, a reversible heat pump is employed to circulate a working fluid via heat exchangers. Under typical functioning circumstances, the system will work in the direction depicted in Fig. 23. When one of the engine fluids (oil, gasoline, or both) reaches a temperature limit, they will change direction to prevent not only the engine fluids from overheating but also the occurrence of undesired physical phenomena, such as cocking, lacquering and varnishing. The design and implementation of this system has its own level of complexity and concerns to consider.

3.4. Environmental control system

The environmental control system ensures a healthy and thermally comfortable environment for passengers and has a significant influence on the energy consumption of the aircraft [68]. The mechanism of ECS can be represented in a generalized form as illustrated in Fig. 24.

The article of Yang and Yang [68] derives an analytical solution for the Coefficient of Performance (COP) of the ECS based on the Endo-reversible Thermodynamic analysis Model (ETM). The study propose a procedure that can reduce design difficulties; however, the gap in this article is the influence of the humidity conditions which can affect the ECS design.

Zimmer [69] presented a robust object-oriented formulation of directed thermo-fluid stream networks. For this publication, the author

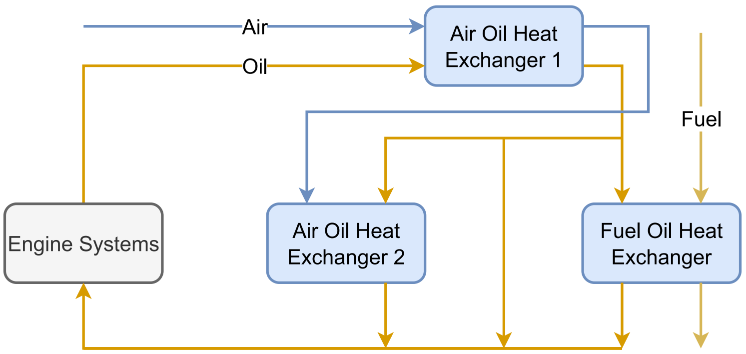

Fig. 22. Thermal management system proposed by United Technologies Corporation.
Source: Adapted from [67].

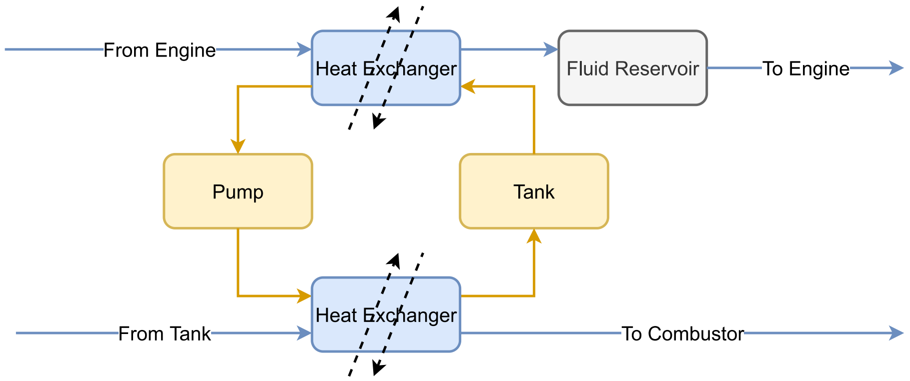

Fig. 23. A reversible heat pump is used in this embodiment to circulate a working fluid through heat exchangers.
Source: Adapted from [67].

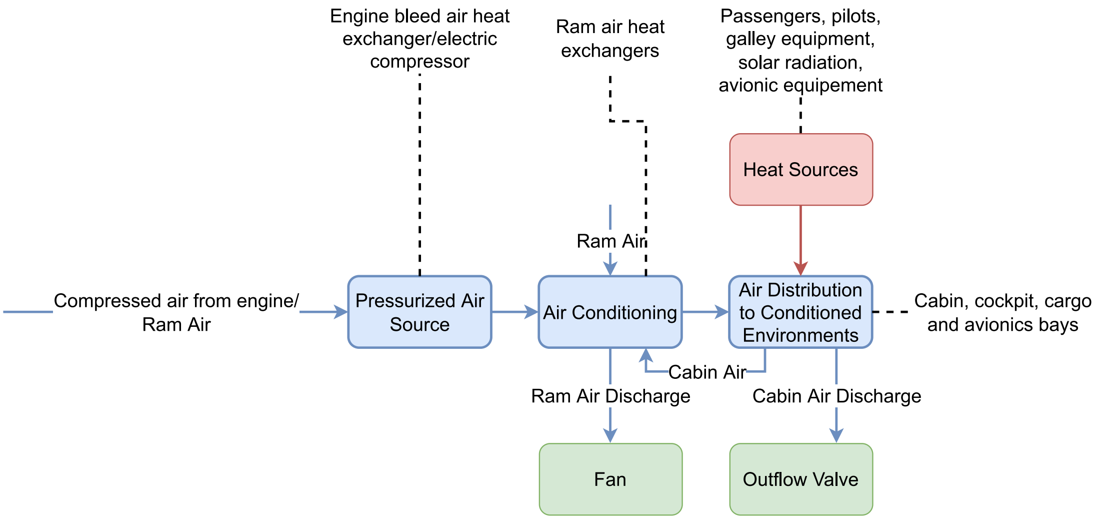

Fig. 24. Generalized environmental system control diagram.
Source: Adapted from [16].

used as an example an aircraft ECS design. The ECS was an electric driven Vapor Cycle Pack (eVCP). This mechanism is compressing the outside ambient air to dehumidify and heat or cool as a function of the desired temperature. For that study they developed a Modelica library/toolbox called HEXHEX, which contains all elements for aircraft environmental control and cooling systems. The schema of the architecture is represented by a Modelica model in Fig. 25.

This complex electric architecture is based in an electric driven vapor cycle pack. From Zimmer's point of view [69] such system designs may replace the air cycle in the future. Another option for the ECS that has been explored is integrating a supplemental cooling system in the vapor cycle [70].

A possibility worth of exploring is to develop a TMS that combines ECS and TMS for the hybrid-electric propulsion system in a synergistic way, i.e., such that the overall mass and energy consumption are minimized. In the study of Perullo et al. [46], the authors proposed to use part of the cold air from the ECS to reduce the BTMS size. This came with an increase of 1.4% in fuel burn despite no mass penalty was

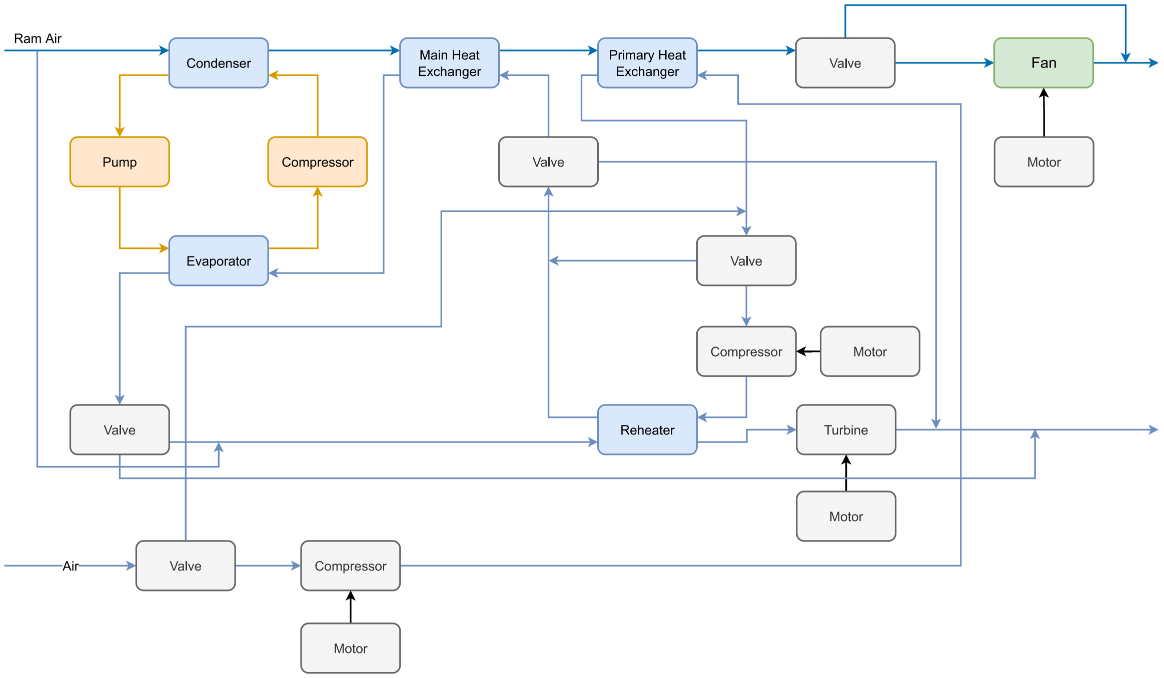

Fig. 25. ECS architecture proposed by Zimmer.
Source: Adapted from [69].

reported regarding the conventional baseline aircraft. Future multidisciplinary solutions might enable larger benefits and reduce the impact of the TMS on both weight and energy consumption of the aircraft.

Also, in the topic of aircraft electrification, recent technology has been developed to offer an alternative for typical ECS air cycle systems that use compressed air of the aircraft engine [71]. In this new concept, a compressor powered by electricity provides the compressed air needed to operate the air cycle unit. There is no need for engine compressed bleed air in such a system. When compared to conventional construction, this shift might result in a 3% reduction in fuel consumption [72]. Further benefits include lower aircraft operating and maintenance costs, greater aircraft overall efficiency, increased system reliability, decreased weight, and decreased carbon dioxide (CO_2) and nitric oxide (NO_x) emissions.

3.5. Sizing methodology

From the literature review here presented, one can clearly point out that an adequate integration, planning, and optimization of thermal management systems are essential for aviation electrification. The best way to accomplish this is through a Multidisciplinary Design Optimization (MDO) strategy to aggregate the most relevant disciplines right from the early design stages. This is particularly important for the next generation of sustainable aircraft as identified by Afonso et al. [73] where only a combination of synergies from different solutions might enable to reach the demanding sustainability goals stated in FlightPath2050.

For hybrid-electric aircraft, given the technological barriers associated to batteries and heat dissipation, it is necessary to account for thermal management systems (and ECS as noted in Section 3.4) through heat transfer models alongside the usually employed disciplines in aircraft design, namely aerodynamics, propulsion, structures, weights, performance, and stability. With this in mind, the flowchart displayed in Fig. 26 represents the authors' vision for sizing the next generation of sustainable aircraft, which includes hybrid-electric ones.

This proposed methodology is a mere illustration of the inputs, design variables and outputs at the disciplinary level that can be used for aircraft sizing. Regarding the simulation models, low-fidelity physics-based models will be preferable at a conceptual level to better explore the design space. On the other hand, more complex high-fidelity numerical models will be essential to fully assess the potential of the obtained aircraft concepts to improve sustainability. Surrogate-modeling [74] and machine learning [75] techniques or even multi-fidelity [76] can be used to mitigate the computational burden of the high-fidelity simulations.

The MDO architecture [77] required to couple all the disciplines is open for debate and will be the focus on forthcoming studies. Currently, efforts have been done to try to couple different disciplines such as thermal-propulsive [78,79] and aero-thermal [80]. Regarding the former, the studies are more at a conceptual level for hybrid-electric aircraft with turbofan [78] and propeller-driven motors [79], while for the latter the studies involve higher fidelity tools [80].

4. Current status, challenges and the future direction of technology

This section sheds light on the current status of the existing TMS technologies (Section 4.1), and provides an outlook for the challenges that promising heat transfer technologies face for their future usage in TMS architectures (Section 4.2).

4.1. Existing technologies

The literature review indicates a trend towards the development of TMS architectures based on a liquid/air system. A more complex architecture is presented for the ULI aircraft [46], where a loop of liquid/air system is combined with a PCM for heat absorption during take-off and climb; and the cold air generated in the ECS enters the TMS of the batteries. In other aircraft, the main difference is in the refrigerant fluid, although the system follows a classical liquid/air system. All the cases reviewed here describe the design of thermal management systems without specifying weather conditions or considering a hot day scenario.

A summary of the TMS architectures proposed for different heat transfer technologies is shown in Table 6, including the number of passengers, propulsion and simulation methods.

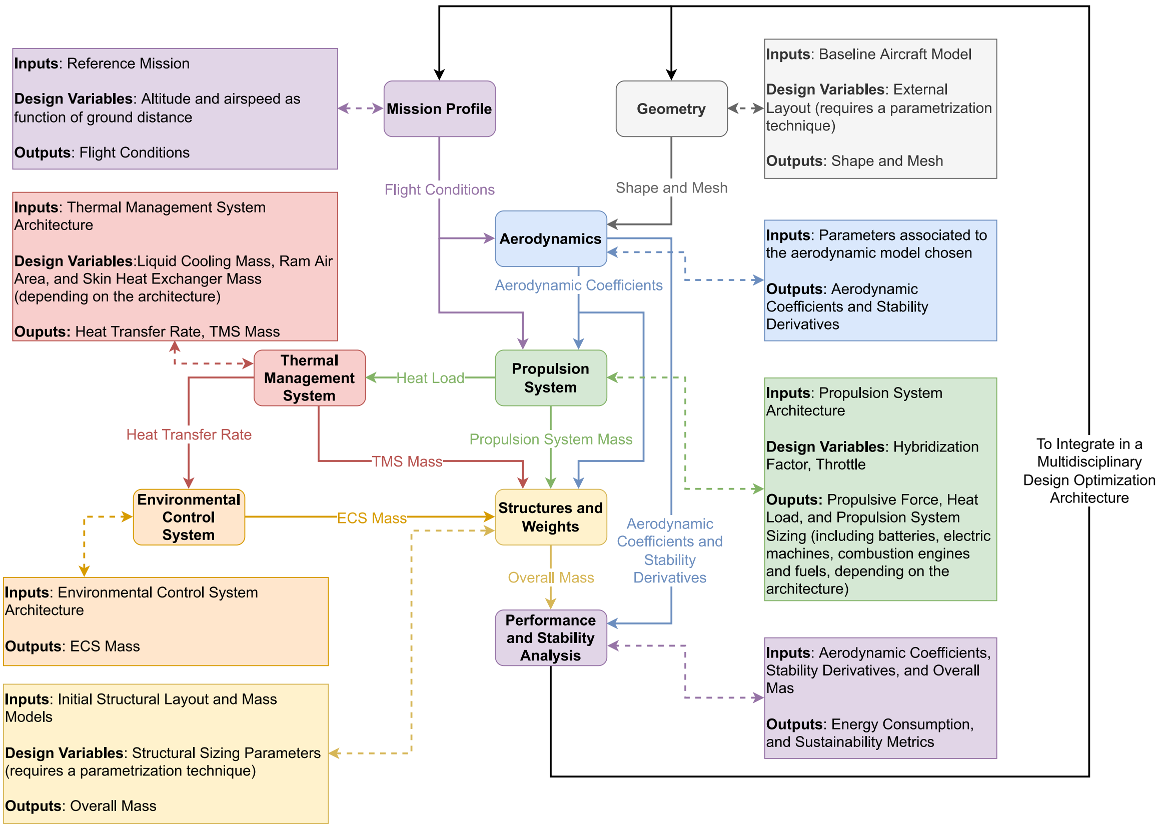

Fig. 26. Proposed sizing methodology.

Table 6
Proposed Thermal Management System (TMS) architectures for different aircraft.

Aircraft	Reference	PAX	TMS	Propulsion	Simulation methods
ECO-150R	[7,8,16,58,81]	150	Liquid/air cooling system	Turboelectric distributed propulsion (TeDP)	Bond graphs (PANTHER)
STARC-ABL	[7–9,11,12,16,61,62,82–84]	154	Liquid/air cooling system	Turbo-electric with an aft Boundary Layer propulsor	Numerical simulation and optimization
RVLT TILTWING	[16,55,82,85]	15	Liquid/air cooling system	Turboelectric	Numerical simulation and optimization
PEGASUS	[7–9,16,55,85–87]	48	Liquid/air cooling system	Turboelectric/Electric	Numerical simulation and optimization
SUSAN	[62,85]	180	Liquid/air cooling system	Electrofan aircraft	Numerical simulation (CAS HEATheR)
HECARRUS	[63]	19	Air-to-liquid (liquid/air cooling system)		Numerical simulation
ULI aircraft	[46,61,83,88]	76	Liquid/air cooling system + two types of PCM + ECS + TMS Battery	Hybrid-turbo-electric distributed propulsion	Bond graphs (NPSS/GT-HEAT)
Short-Range Partial-Turboelectric Aircraft	[11]	180	Ram airbased	Partial-turboelectric	Numerical simulation
Parallel Hybrid Quadrotor	[16,82,85]	6	Liquid/air cooling system	Hybrid Propulsion System	Bond graphs (NPSS)
Hydrogen-Powered Propulsion Technologies	[9,16,64]	n/a	(1) Exhaust gas heat exchanger. (2) Exhaust gas heat exchanger, compressor intercooling, turbine air cooling heat exchanger, and flow expander in configuration. (3) Exhaust gas-to-fuel heat exchangers use exhaust heat to raise fuel temperature while lowering exhaust gas temperature, as a result, exhaust noise.	Hydrogen-Powered Propulsion	

Table 7
Technologies with low technology readiness levels.

New trends	Important studies
New heat exchangers	[16,89]
Nanofluids	[52,90]
Superconducting Machines and Cryogenic Coolants (LH2)	[64,91–93]
Outer Molder Line cooling	[12,94,95]
Additive Manufacturing	[96–100]
Ammonium Carbamate as heat sink	[101–104]

4.2. Promising low TRL technologies

New TMS solutions for more electric commercial aircraft have been proposed and studied in the recent years as the knowledge on such aircraft has grown. Some of these TMS solutions are still far from being ready for onboard integration in the forthcoming years. Nevertheless, some of them have already shown great potential at low TRLs and thus they are seen as promising for the future.

Recent research has focused on boosting the efficiency of heat exchangers by adding fins and micro-fins, modifying the shape, and/or changing the construction materials. This is done to reduce negative performance impacts by reducing pressure drop and to make better use of volume [16]. The discussion on this topic focuses on how innovative heat transfer surface designs may result in improved heat transfer and decreased pressure drops for heat exchangers. Some of the recent studies carried out in this field are described in Table 7. One specific configuration has recently emerged: **microchannel heat exchangers**. They represent a good opportunity for the TMS thanks to their better heat transfer, reduced weight, and possible space, energy, and material savings over the standard heat exchanger equivalents [89].

The goal of many recent research has been on whether **nanofluids** can be utilized as a substitute for the usual coolants or not. When compared to traditional coolants like water and ethylene glycol, which have poorer thermal conductivities, nanofluids made of nanoparticles suspended in base fluids may provide improved thermal conductivity and heat transfer performance [90]. The enhanced overall heat flow rate in the presence of nanoparticle concentrations is due to a higher collision rate between nanoparticles and channels walls of the heat exchanger. Most of the studies (Table 7) in this area have concluded that using nanofluids, the heat transfer performance increases, and as the nanoparticle's concentration increases, so do the convective heat transfer coefficient.

Other important topics to highlight are the **superconducting devices** and **cryogenic coolers**. To gain an advantage by using hybrid-electric propulsion systems on such aircraft, low mass and high efficiency of the electric components are required, which are difficult to achieve with the current state of the art technology. These constraints might be solved by using superconducting and cryogenic-cooled components. Employing superconductors in electric machines or cables might minimize the bulk and needed voltage levels of such components owing to their large current carrying capacities [91]. Hydrogen in a liquid state has a cryogenic temperature at the level of 20–25 K. This feature enables LH2 to be used to cool superconducting electrical devices [92]. When these components are cooled with liquid hydrogen, the evaporated hydrogen may be employed as a fuel for power production (fuel cells). Using (liquid-) hydrogen instead of kerosene to generate power and thrust in airplanes has been the subject of various studies in the past, some of them presented in Table 7. According to research studies, employing hydrogen decreases CO2 emissions while also enhancing engine efficiency. However, the space necessary to hold the requisite quantity of liquid hydrogen in the aircraft, owing to its low volumetric density, creates a challenge at an aircraft-level. The cryogenic technology for airplane propulsion would unlikely be accessible within a 30-year timescale [93].

Still within the topic of hydrogen as a fuel, it is known that thermal management is a major issue for fuel-cell-powered commercial jets. Fuel cells have an efficiency of about 50% and therefore, according to Filipenko [94], in the case of an A320-size airplane, around 20 MW of heat would have to be rejected by heat exchangers. Aside from the heat-exchangers' huge weight (including pumps and other components), their drag at Mach 0.8 would be enormous. However, in light of the most recent research into what is known as **Outer Mold Line (OML) cooling**, this picture might significantly shift [95]. Instead of employing heat exchangers, the aircraft's outside skin is employed to reject heat. It does so by having a system of pipes through which the cooling liquid needed to cool the fuel cells and the powertrain is circulated and re-cooled. Up to 18 kW of heat may be rejected and, in terms of weight, an OML cooling system does not seem to have a significant detrimental influence on overall aircraft performance. Also, the benefit of this approach is that the aircraft's outside form is only slightly changed, resulting in a smaller amount of extra drag from heat-rejection.

The advent of **Additive Manufacturing (AM)** has brought a new strategy for heat rejection, particularly in the development of novel alternatives to the traditional heat sinks. AM can be used to produce complex designs without the traditional manufacturing constraints. AM allows to create heat transfer devices that can be designed to increase and optimize the performance for conduction, convection and radiation. Channels with complex internal cavities and bio-inspired designs are examples of such devices that act as heat sinks. Certain AM technologies often result in inherently rough surfaces, which allow for more heat transfer to occur. The main goals of developing AM heat sinks are the desire to reach the maximum cooling, the minimum heat loss or the ratio of maximum cooling per loss [96].

One of the main advantages of AM is the possibility to manufacture complex geometries arising from a topology optimization problem set for a given objective. Topology optimization is an advanced structural design method which aims to obtain the optimal structural layout for a given objective by means of adequate material distribution within the design domain, while satisfying a set of constraints. These may include performance requirements for different load conditions. In the aerospace sector, this technique has been applied to design not only lightweight structures with high-performance, but also multifunctional structures [97,98].

Heat sinks techniques such as liquid-cooled microchannel [99] or microchannels associated with PCM [100] were developed in recent years using topology optimization for AM to increase the heat rejection in electronic equipment.

Another possibility is to exploit the endothermic chemical-based reaction of a suitable reversible compound to act as a heat sink. Unlike the phase change such a compound will allow for a larger enthalpy change [105]. One of these compounds is the **Ammonium Carbamate** (AC) whose reaction temperature, between 10 °C and 60 °C [103], is within the range of normal battery operating temperatures. The by-products of this reaction are carbon dioxide and ammonia gases with an enthalpy of approximately 2 $\mathrm{MJ\,kg^{-1}}$, which is comparable to the water vaporization at atmospheric pressure [103]. However, this solution still faces some challenges, namely in what concerns how to control the reaction temperature, as noted by Johnson et al. [103].

5. Concluding remarks

The literature review has enabled the identification of several factors that influence the choice of different technologies for the design of a TMS architecture. The type of aircraft (hybrid or electric), the amount of heat produced/released by the various components and the TRL of heat transfer technologies, are all factors that influence the performance and design of the TMS architecture. One of the main challenges of designing a TMS, is to integrate the different heat transfer technologies to guarantee the required heat transfer functionality and, at the same time, the minimal negative impact to the overall aircraft efficiency and performance.

The majority of the TMS topologies researched for hypothetical airplanes presented in this literature overview used liquid cooling loops as transport systems. This technology must be associated with a fluid with a high thermal capacity, such as Polyalphaolefin (PAO), PGW30 or PSF-5 (and in the near future nanofluids), which allows to remove a greater amount of heat from the various components. These liquid cooling loops may be integrated with different heat transfer technologies. According to the literature, ram air is the most common solution since it is already a consolidated technology at aircraft level. However, this intake of air can create a considerable drag penalty. Skin heat exchangers are an alternative that make use of the already available aircraft outer surface having low impact on drag, power and mass. Using fuel (in the case of a hybrid electric propulsion architecture) as a heat sink is also a possible approach since the waste heat is utilized for purposes where heat is required, in this case, heating fuel prior to combustion, promoting optimal energy management and reducing the detrimental effect on efficiency. Using new manufacturing techniques and innovative shapes may increase the heat transfer efficiency in heat exchangers and the overall system performance.

As a final remark on thermal management strategies and given the complexity and multidisciplinary nature of adequately integrating these strategies in future hybrid-electric aircraft, it is the authors' recommendation to conceive MDO architectures that encompass the key disciplines, including heat transfer, essential to mitigate the environmental impact while extracting the highest performance possible.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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