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Thermal management challenges in hybrid-electric propulsion aircraft

Majid Asli [a,*], Paul König [a], Dikshant Sharma [a], Evangelia Pontika [b], Jon Huete [b], Karunakar Reddy Konda [a], Akilan Mathiazhagan [a], Tianxiao Xie [a], Klaus Höschler [a], Panagiotis Laskaridis [b]

[a] Chair of Aeroengine Design, Brandenburg University of Technology Cottbus-Senftenberg, Siemens-Halske-Ring 14, Cottbus 03046, Germany
[b] Centre for Propulsion and Thermal Power Engineering, Cranfield University, Bedfordshire MK43 0AL, United Kingdom

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ABSTRACT

The utilization of hybrid electric propulsion concept in aviation offers a viable solution to address the limitations posed by the relatively low energy density of batteries in fully electric aviation. These hybrid systems enable the aircraft to achieve a significant range while simultaneously minimizing carbon emissions. While the individual components of a Hybrid Electric Propulsion (HEP) system, such as electric motors and batteries, are designed with high efficiency, their integration presents a significant challenge in the realm of thermal management. Designing an efficient system for managing the substantial waste heat generated by heat sources and effectively transferring it to heat sinks during various flight phases is a complex task. This challenge becomes even more critical as the design must adhere to system weight limits and prioritize aviation safety considerations. In this review article, we performed a systematic review of the challenges related to the key elements in a thermal management system. These elements encompass every component or subsystem that contributes to the thermal management of a generic hybrid-electric propulsion system. This includes electric motors and generators, batteries, heat exchangers, power transmission systems, power distribution systems, storages, fuel cells, cooling fluids and pipes, control system, pumps and fans. Following the identification of the challenges, the paper provides a comprehensive summary of the existing solutions that have been offered and pursued by the community to address the challenges. Furthermore, the paper also discusses emerging technologies related to each element, highlighting their potential in overcoming these challenges.

1. Introduction

Global aviation, accounting for approximately 2.5% of global emissions, would secure a position among the top 10 emitters if it were treated as an independent country [1]. The increasing demand for air travel [2], coupled with growing public awareness of global climate change, has prompted legislators and policymakers to prioritize the development of a climate-friendly aviation industry. The latest agreement, known as the European Green Deal, sets a target of achieving climate neutrality in Europe by the year 2050, with an intermediate milestone of at least a 55% net reduction in greenhouse gas emissions by 2030. Accordingly, researchers and manufacturers are looking into the potential solutions for green aviation, among others, hydrogen combustion [3,4], fuel cell technology [5–7], using sustainable aviation fuels [8,9], and electrification [10,11].

As a disruptive innovation in the propulsion system of aircraft, all-electric and hybrid-electric propulsion aircraft have garnered significant attention. These innovative aircraft designs utilize electric or hybrid-electric propulsion systems, which offer potential advantages in terms of reduced emissions, improved fuel efficiency, and quieter operations compared to traditional combustion engine aircraft. Although all-electric propulsion systems are ideal for an aircraft, taking into account the very low energy density of the current battery technology, making a medium-range flight on a pure electric propulsion system is unlikely to achieve in a decade. Epstein and O'Flarity [12] showed that if the battery pack energy density reaches 800 Wh/kg, flying an all-electric narrow-body aircraft, e.g. A320, can be feasible. The hybrid-electric propulsion system concept, in this context, mitigates the reliance of the aircraft on the energy density of the batteries by combining electric propulsion with traditional combustion engines or fuel cells. In these designs, electric motors work in conjunction with combustion engines, which can be fueled by conventional, hydrogen or sustainable aviation fuels. The electric component supplements the power provided by the combustion engine, enhancing efficiency and reducing emissions. Still, there are some crucial challenges to be addressed in the early design phases to unblock the full potential of HEP technology and realize the benefits in terms of sustainable aviation,

* Corresponding author.
E-mail address: asli@b-tu.de (M. Asli).

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namely heat management system to dissipate the heat released by the components [13], high power density energy storage [5], efficient power management system for balancing power requirements between electric motors, combustion engines, and other auxiliary systems [14,15]. The two former contribute to the overall mass of the aircraft significantly resulting in a higher maximum take of weight, therefore a higher thrust demand, and hence the need for higher energy resources, creating a closed loop over the aircraft weight. The present paper is focusing on thermal management challenges.

In recognition of the significance of Thermal Management System (TMS), researchers have recently made concerted efforts to consolidate and synthesize the exploration of relevant technologies through the creation of review articles. Heerden et al. [16] provided a general overview of the thermal management system in a conventional aircraft. They classified the broad topic of TMS into five major elements of heat sources, heat acquisition mechanisms, thermal transport means, heat rejection mechanisms, and heat sinks and the technological aspects that can be employed to facilitate the design of TMSs were discussed. In addition, they have identified some critical topics that hold significant priority in the research on general aircraft thermal management, namely thermal management in (i) all/hybrid-electric propulsion aviation [13], (ii) ultra-high bypass ratio geared turbofans [17], (iii) high-power military systems which use considerable power and produce large amounts of waste heat [18], (iv) environmental control system as essential and large onboard secondary power consumer [19], (v) integrated power and thermal management systems [20,21], and (vi) supersonic transport aircraft which has high thrust demand while exposing to aerodynamic heating [22,23]. While the article presented a wide literature review, it did not delve into the specifics of TMS in HEP configuration due to the overarching breadth of the topic. In another review article on the general TMS topic, Srinath et al. [24] explored thermal management system architectures proposed for hydrogen-powered propulsion technologies including fuel cell-powered aviation. Combining TMS with the engine fuel system, and potentially compressor intercooling, turbine air cooling heat exchanger, and flow expander has been suggested as the envisioned architectures for future hydrogen-powered aircraft. Coutinho et al. [13] have recently reviewed the recent developments in TMS for hybrid-electric aircraft. They have collected heat transfer technologies with a focus on assessing their technology readiness level, thereby pinpointing the associated challenges and opportunities. This spans from widely used liquid and air cooling to cryogenic cooling and thermoacoustic heat engines with a very low Technology Readiness Level (TRL). Recent development in the key components of TMS, i.e. batteries, electrical machines and combustion engines and fuel cells have been discussed concentrating on different TMS architectures. As a conclusion, promising low TRL technologies playing a role in TMS have been outlined namely microchannel heat exchangers [25], nanofluids as coolant [26], superconducting devices and cryogenic coolers which can take advantage of liquid hydrogen [27,28], outer mold line (OML) cooling using aircraft's outside surface to reject heat [29], additive manufacturing techniques enabling the construction of complex heat exchangers optimized for specific applications [30], and employing endothermic chemical reactions (e.g. ammonium carbamate) as expendable heat sinks [31]. As part of preparing a roadmap for a 50-passenger regional airliner, Affonso Jr. et al. [32] tried to identify some potential strategies to tackle the TMS challenges, in particular, reuse of waste thermal energy for other purposes in aircraft e.g. aircraft environmental control system, energy harvest by thermoelectric generators, intelligent use of aircraft heat sinks, and thermal accumulators using phase change materials in order to store and reuse the heat energy.

Despite the significant efforts dedicated to various aspects of TMS cited above, there is a need for a systematic review specifically focused on TMS in the context of HEP, with a particular emphasis on components and subsystems. While prior research has explored different facets of TMS, such as heat transfer technologies or thermal management system architectures, there remains a gap in the review literature when it comes to a holistic examination of TMS components within the HEP domain. Addressing this gap would involve conducting an in-depth review that considers the specific requirements, challenges, and advancements related to TMS components and subsystems. Therefore, the objective of the current paper is to shed some light on the recent efforts on thermal-related challenges of the components involved in HEP spanning from big ones, e.g. electric motors, to small ones, e.g. pipes and fans, with the aim of providing a centralized and updated source of information to empower researchers and designers in identifying the bottlenecks and hence developing effective designs and practical solutions.

In order to conduct a thorough and comprehensive review, the selection of components for analysis was based on the general architecture prevalent in HEP. This architecture encompasses various propulsion systems, including parallel, series, and turboelectric propulsion systems. Fig. 1 provides an overview of the key elements playing a role in TMS and are part of the broader HEP system, showing thermal and mechanical interconnections. The term "element" in this paper is defined as any component or subsystem within the HEP that either has a thermal contribution within the system and needs to be thermally managed or plays a role in thermal management. It should be noted that although gas turbine engine can be a part of a HEP system, it is excluded in this paper since it has its own very well-developed thermal management system [33] and hence is out of the scope of this paper. This introduction is followed by ten sections providing a detailed state-of-the-art and recent advancements of the elements shown in Fig. 1, i.e. Thermal management systems in Section 2, Motors and generators in Section 3, Heat exchangers in Section 4, Batteries in Section 5, Power electronics in Section 6, Pumps and fans in Section 7, Fuel cells in Section 8, Cables in Section 9, Coolants and plumbing in Section 10 and Hydrogen storages and tanks in Section 11. In each section, following a description of the element and its role in TMS, the main specifications are explained and the associated challenges and recent developments, highlighting emerging trends in the field, are discussed.

2. Thermal management system

Thermal management system is important to maintain the propulsion system components at optimal operating temperatures. All the components related to the TMS can be broadly classified as the elements that require TMS and elements that enable it. Electrical components, e.g. batteries and motors, falls in the first category whereas components such as fans, pumps, cooling loops, and heat exchangers, belongs to the latter [16]. Design of an efficient TMS is a multivariable optimization problem. The main challenge is developing a light weight TMS that results in lower cooling drag and fuel penalty considering the large heat loads observed in electric propulsion. An optimal design should also perform effectively at all aircraft operating scenarios [13]. Different TMS architectures produce different outcome in terms of weight, fuel consumption and drag. The weight of the TMS mainly includes the weight of pumps, fans, heat exchangers, pipes, tanks and valves. Basically, the TMS weight depends on propulsion system configuration, energy management in a mission, selected cooling technologies, and component positioning. The fuel penalty depends on the operation of pumps and fans and drag depends on the operation of air flow path. A system with fan driving the air flow and no ram effect require more power and results in less drag whereas a system in which air flow is driven by ram effect and has no fan results in less power requirement and more drag. Modeling and design trade off studies for various TMS architectures were published by several researchers in the literature [34–45].

The TMS layout or architecture is application specific and making a generic classification is not easy. The TMS can be centralized with a single heat exchanger dissipating all the heat or decentralized with multiple coolant loops and heat exchangers. The coolant flow can

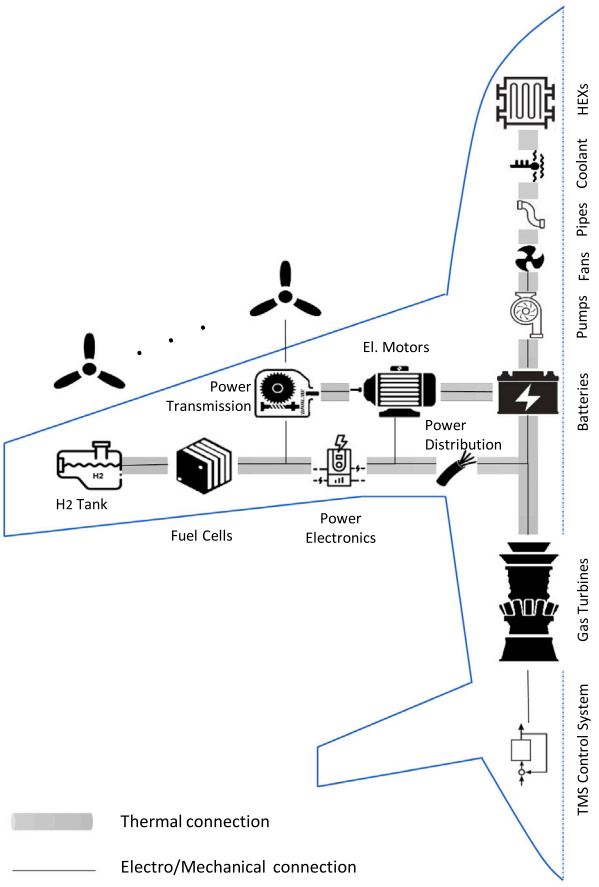

Fig. 1. An overview of the primary subsystems and components within a thermal management system in a general HEP aircraft.

be 'series' cooling one component after another or 'parallel' cooling different components simultaneously. Table 1 summarizes some major TMS architectures reported so far by researchers. The main features of all the architectures are also presented for comparison. Representative TMS architectures are shown in Fig. 2.

2.1. TMS design trade-offs

Rheaume and Lents [34] designed a thermal management system for a 5 MW parallel hybrid electric propulsion system. They predicted from the simulation results that the TMS increases the fuel consumption during take-off, climb and cruise phases by 3.4%. Rheaume et al. [35] extended their earlier work and proposed alternative architectures and approaches to improve the performance of the TMS compared to the system in [34]. The weight of the ram air cooled heat exchangers was reduced to 20% by having separate cooling loops for battery and motor drive and utilizing the battery thermal mass for heat storage. The battery ram air cooled heat exchanger was sized for a operating point at 20 kft altitude. The fuel consumption penalty over the aircraft mission due to TMS weight, power consumption and drag is predicted to be 0.75%. They also carried out the weight sensitivity investigations [36]. Assuming a 1% improvement in battery efficiency and 2% improvement in motor efficiency, the weights of the battery and motor drive ram air heat exchangers were predicted to reduce by 26% and 38% respectively. The ram fan weight was estimated to decrease by 48% when the battery heat exchanger is sized for a operating point at 20 kft. The reference hybrid propulsion and baseline (geared turbo fan engine) propulsion systems for all these studies are presented in Ref. [46].

A TMS with a specific cooling capacity of 0.79 kW/kg was designed and evaluated for a battery powered aft fan engine in [37]. A 21.3% increase in TMS weight was predicted when redundancy is considered in the TMS design and additional backup components are added. An optimization study to minimize TMS related fuel burn penalties for a series hybrid propulsion system in the design space of Beechcraft King Air C90GT aircraft was carried out in [38]. It is shown that the turboelectric aircraft has modest TMS related penalties whereas hybrid-electric aircraft has the largest penalties mainly due to the differences in battery heating/cooling and propulsion system requirements. Kellerman et al. [39] investigated the impact of a ram air based TMS on aircraft mass, drag and fuel burn for a 180 passenger short range turboelectric aircraft. They concluded that increasing electric component operating temperature limits eliminate cooling drag in cruise phase. Also, oversizing the TMS can avoid the need to use fan but increases the fuel burn by 0.29%. It is estimated that the mass of TMS can increase by 100% if redundancy (back up) for TMS components is considered. Chapman et al. [40,41] developed TMS concepts for 3 different electric propulsion concepts: urban air mobility (turboelectric), regional mobility (full electric) and single aisle (turboelectric) aircrafts. The TMS were designed for both the state of art and advanced electric component technologies. Sensitivity studies were carried out to study the impact of changes in altitude, heat loads, component temperature limits on the TMS weight, drag and power requirement. A 1.5% and 2.5% increase in converter and motor efficiencies respectively, along with the usage of AC bus eliminating rectifier is shown to reduce the TMS weight by 50%. Also, different weightage to drag, weight and power in the objective function to optimize TMS resulted in different TMS designs. A thermal management system with thermoacoustic refrigerator to cool the battery in a hybrid electric propulsion was proposed in [42]. It was concluded that a vapor cycle TMS performs better or comparable to the thermoacoustic system for the considered mission. Integrated system level analyses were carried out by some researchers to arrive at an optimal vehicle level performance i.e., optimal interactions between the propulsion system and TMS [43–45]. Abolmaoli P.C. et al. [43] explored the fuel consumption savings by an integrated study of propulsion and thermal management systems. They showed a 750 lb fuel savings in hybrid electric propulsion compared to a conventional turboprop engine for a 18 h long flight mission. Kim et al. [44] also performed an integrated system level analysis to assess the implications of introducing an electrical power train and the associated TMS on fuel burn and take-off weight for a turboelectric propulsion system. Three different TMS architectures were proposed in this study: (a), fuel cooled (b) cooling using vapor compression (VCS) cycle, and (c) a hybrid cooling method using fuel cooling for higher heat loads and VCS for lower heat loads. The hybrid system and fuel cooled system resulted in lowest weight and power consumption respectively whereas VCS cooling is the worst in both the parameters. It is concluded that the propulsion and thermal management systems are not feasible at the current state of art power densities. They also showed that the TMS penalties outweighed the benefits of hybrid electric concepts even with improved power densities proving the need for advancements in heat transfer technologies. Shi et al. [45] designed a TMS for a turboelectric aircraft (NASA ULI) and investigated its operation and impact on engine performance over the entire mission. They concluded that a typical oil air based thermal management system may not provide sufficient cooling in the early mission phases like take-off and climb. It was suggested to employ additional coolant or phase change material (PCM) during these phases. Also, it was found that using additional coolant has greater fuel burn, weight penalties compared to utilizing PCM.

The TMS design and performance depends on various factors as explained above. It can be observed from the literature that the studies carried out so far are based on a lot of assumptions and are application specific. Weight reduction, heat transfer improvement, drag and fuel consumption reduction are the TMS design challenges every researcher agrees on. These challenges, if not properly addressed make

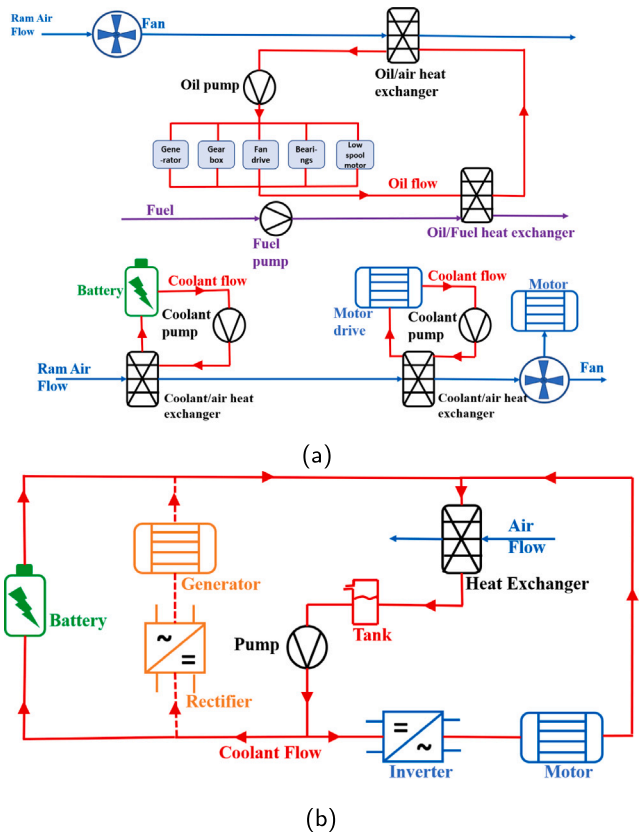

Fig. 2. Two different TMS architectures, (a) and (b) are adapted from [35] and [37] respectively.

the (hybrid-) electric propulsion infeasible. The increase in power densities and efficiencies of electrical components will not mitigate the TMS-related challenges completely considering higher power magnitudes required in aircraft applications. Inherent TMS-related advancements e.g., a heat exchanger with improved heat transfer, reduced weight and ram drag or a lighter pump/fan requiring less power or advanced heat transfer technologies [47], or an efficient ram air recovery [44], or lighter piping system are necessary to realize the benefits of electric propulsion.

3. Motors and generators

The general operating principle of electric motors is based on the interaction of electric current and magnetic fields to provide torque, speed and thus power. A common categorization exists at different levels and comparisons for the usability of electric motors can be made in different ways. These include:

- Brushed and brushless motors,
- Synchronous, asynchronous and reluctance motors (brushless) or
- Wound field and permanent magnet motors (synchronous).

To evaluate the applicability of these motor types for MEA and HEP applications, metrics can be used to qualitatively assess losses, thermal and mechanical limitations, achievable power and current densities, complexity or short-circuit behavior and identify suitable candidates. The achievement of these metrics is more difficult in HEP applications, as more power has to be converted compared to MEA. In a study by Ganev additional metrics were used and Permanent Magnet Synchronous Motor (PMSM) were identified as the most suitable candidate for MEA and thus for HEP [48]. Other studies came to the same conclusion [49].

3.1. Losses

Losses cause reduction in efficiency during the conversion from electrical to mechanical power (motor) or vice versa (generator). They manifest themselves either as a direct heat source or indirect heat source by causing increased energy consumption and reducing the efficiency of the machine.

In real machines, joule losses occur primarily. These are usually divided into copper losses, excitation losses and brush transition losses. Copper losses P_{Cu} refer to those losses caused by the flowing current I (direct current or root mean square value of alternating current) and the electrical resistance R in windings, see Eq. (1).

$$P_{Cu} = I^2 \cdot R \tag{1}$$

Excitation losses P_{Ex} occur in electrical circuits of an excitation winding including the associated slip ring transmission and external variable resistors, expressed in Eq. (2). No rotational voltages are induced in excitation windings, however, they build up electric fields.

$$P_{Ex} = U_E \cdot I_E \tag{2}$$

Brush transition losses P_{Br} occur in the part of the winding which is connected to the external supply line by means of a sliding contact and exists and carries current due to a voltage drop across these brushes. The voltage drop U_B is not proportional to the current I, shown in Eq. (3).

$$P_{Br} = U_B \cdot I \tag{3}$$

Iron losses P_{Iron} occur everywhere in the magnetic circuit where time-varying inductions are present. They consist of hysteresis P_{Hyst} and eddy current losses P_{Eddy}, Eq. (4). Hysteresis losses are linear, eddy current losses are quadratically dependent on the frequency.

$$P_{Iron} = P_{Hyst} + P_{Eddy} \tag{4}$$

Friction losses P_{Fric} can occur due to bearing friction, brush friction and air friction. Air friction losses include rotor air friction losses (windage) and the power requirements of any cooler attached to the machine shaft.

The last type of loss to be mentioned is additional losses P_{Add}. In contrast to the previous losses, these are difficult to determine in terms of their place of origin, since their cause is not directly related to the operating principle of the machine. For quantification, typically certain tests/experiments are run to determine the aforementioned losses. The measured total loss is reduced by these portions, so that the rest is defined as additional loss [50].

The speed and torque of electric motors can usually be controlled independently, resulting in the requested mechanical output power according to the flight mission. This allows heat generation due to losses to be influenced and addressed during the design process and in the control scheme. A typical loss distribution for a PMSM is shown in Fig. 3. It is clear that joule losses (copper losses in the windings) dominate in all cases. In operating conditions with high speeds (maximum speed condition), the mechanical losses increase significantly due to bearing and air friction. In phases in which high torque is required (peak load), the proportion of current-related losses increases significantly.

3.2. Cooling

The permissible over-temperature of electrical machines is primarily limited by the low heat resistance of the insulation materials used on the windings to electrically insulate them. Insulating materials are typically characterized by insulating material classes, with class H according to IEC 60085 [52] allowing a maximum local temperature of 180 °C and representing the upper temperature limit in most machines. In addition, exposure to elevated temperatures can also lead to

Table 1
Different TMS architectures and their specifications.

HEP architecture and power level	Type of cooling and coolant loops	Heat sink	Reference
Parallel Hybrid (twin engine), Motor power — 2.1 MW	• Oil cooling loop for high temperature heat loads (parallel) • Coolant (50% Propylene Glycol–Water) loop for battery & motor drive (series) • Air cooling for motor	• Oil loop — Oil/fuel heat exchanger • Coolant loop — coolant/ram air heat exchanger	[34]
Parallel Hybrid (twin engine), Motor power — 2.1 MW	• Oil cooling loop for high temperature heat loads (parallel) • Coolant (50% Propylene Glycol–Water) loop1 for battery • Coolant (50% Propylene Glycol–Water) loop2 for motor drive • Air cooling for motor	• Oil loop — Oil/fuel heat exchanger • Coolant loops — coolant/ram air heat exchangers	[35,36]
Series–parallel (tri engine), Batter power — 500 kW	• Coolant loop (parallel) • Path1 — splits into two sub paths. Sub path1 is for rectifier and generator and sub path2 is for battery • Path2 — for inverter and motor	• Coolant/ram air heat exchanger	[37]
Turboprop + Turboelectric, Generator — 2 MW	• Coolant loop (parallel)	• Coolant/ram air heat exchanger	[39]
• Turboelectric single aisle aircraft (STARC - ABL) • Turboelectric tiltwing UAM • Full electric regional mobility aircraft (PEGASUS)	• Single Aisle Aircraft & UAM (for current technology levels) – Oil cooling loop for generators and engine (series) – Coolant loop1 (30% propylene glycol–water) for rectifier – Coolant loop2 (30% propylene glycol–water) for motor and inverter (series) • Regional mobility aircraft (for current and future technology levels) – Coolant loop1 (30% propylene glycol–water) for battery – Coolant loop2 (30% propylene glycol–water) for motor and inverter (series)	• Single Aisle Aircraft • Oil loop — Oil/Fuel and Oil/ram air heat exchangers • Coolant loops 1 & 2 — Coolant/ram air heat exchangers • UAM • Oil loop — Oil/ram air heat exchanger • Coolant loops 1 & 2 — Coolant/ram air heat exchangers • Regional mobility aircraft • Coolant loops 1 & 2 — Coolant/ram air heat exchangers	[40]
Parallel Hybrid, Motor — 1 MW	• Coolant (glycol–water) loop — for motor • Thermoacoustic refrigeration cycle — for battery	• Coolant loop — coolant/ram air heat exchanger • Refrigeration cycle — chiller and coolant/ram air heat exchanger	[42]
Series Hybrid, Generator power — 800 kW	• Fuel cooling loop for motor & generator (series) • Coolant loop (Polyalphaolefin) for aircraft auxiliary heat loads (series) • Air cooling for battery	• Fuel loop — Fuel/ram air heat exchanger • Coolant loop — Coolant/ram air heat exchanger	[43]
Turboelectric distributed propulsion (4 independent electrical power trains), Generator power — 11.25 MW	• TMS Architecture 1 — Each component (motor, generator, inverter, rectifier and electric bus) has its own cooling loop • TMS Architecture 2 — Each component (motor, generator, inverter, rectifier and electric bus) has its own vapor compression cycle cooling • TMS Architecture 3 — A hybrid version of above 2 architectures i.e., separate fuel cooling loops for generator and rectifier, separate vapor compression cycle cooling for bus, motor and inverter	• TMS Architecture 1 — A fuel/ram air heat exchanger in each loop • TMS Architecture 2 — A refrigerant/ram air heat exchanger in each cycle/loop • TMS Architecture 3 — A refrigerant/ram air heat exchanger or fuel/ram air heat exchanger in each loop	[44]
Turboelectric, Motor — 2.1 MW	• Coolant (Polyalphaolefin, series) loop — for motor, motor drive and inverter	• Coolant loop — Coolant/fan bleed air heat exchanger	[45]

irreversible demagnetization of permanent magnets and reduced performance due to deterioration of the windings [53,54]. To counteract these effects, various cooling methods can be applied to the rotor and stator to ensure safe operation. Cooling methods can be divided into air cooling, liquid cooling and PCM cooling. Depending on the design and application, different cooling methods have different advantages and disadvantages in terms of their thermal effectiveness. An overview of various HEP and all-electric aircraft machines with their cooling strategy has been presented in Table 2.

3.2.1. Air-cooled

Convective heat transfer utilizes the motion of a fluid (air or water) to carry away heat from source to sink. Air in natural/ passive air-cooled systems gathers heat from the hot motor parts, becomes less dense and rises [61]. Simplicity of design in a natural air-cooling system due to no pumping requirements, low leakage losses and less weight makes it an efficient cooling scheme for small-scale (< 10 kW) and medium-scale (10–100 kW) HEP applications [62]. Heat transfer coefficients (HTCs) up to 25 W/(m^2 K) [63] can be achieved. Forced convection of gases/air requires certain fan and pumping equipment

Table 2
Electrical machines for HEP and all-electric aviation.

Electrical machine	Power class	Cooling	Location	Features	Challenges	Reference
Radial flux PMSM	60 kW	Forced-air	• Stator cooling fins • Intra-coil core gap	• Lightweight • High heat transfer • Good efficiency (95%)	• High pressure drop	[55]
Outer rotor PMSM	1 MW	Forced-air	• Air-gap winding • Stator heat sink	• Litz wire winding • High efficiency (>96%) and power density (>13 kW/kg) • Lower iron losses • Lightweight	• Design complexity • Mechanical risks	[56]
Axial flux PMSM	1 MW	Hybrid (liquid + potting)	• Stator cooling jacket (aluminum jacket with automatic transmission fluid as coolant) • End-windings potting material (epoxy resin) • Shaft liquid cooling (automatic transmission fluid as coolant)	• High heat dissipation • Robust • Integration with PE cooling	• Heavyweight and complex system • Mechanical vibrations • Safety issues due to leakage	[57]
Permanent Magnet Synchronous Generator	4 MW	Liquid	• Slot cooling channel • End-windings oil jet impingement • Stator oil jacket	• Litz wire winding • High efficiency (98.3%) and power density (20 kW/kg) • High cooling capacity • Flux density improvements	• Heavyweight and costly • Complex architecture • Leakage losses	[58]
Wound field synchronous machine	1.4 MW	Hybrid (liquid + cryogenic)	• Stator direct liquid cooling • Rotor cryogenic cooler • Cryo-cooled superconducting coil	• Litz wire winding • High efficiency (>98%) and power density (>16 kW/kg) • Lower iron losses • Lightweight	• Heavyweight and complex design • High rotational speeds can affect cryo-cooling operations • Centrifugal rotor stress • High rotor heat load	[59]
HTS Homopolar Inductor Alternator	1.3 MW	Hybrid (liquid + cryogenic)	• Stationary coil gravity-fed boiling liquid neon cooling • Air-gap winding liquid cooling (water or dielectric fluid) with ceramic cooling tubes	• Power density (>8.8 kW/kg) • HTS coils provide a high magneto-motive force • Robust design	• Leakage flux in interpolar spaces • Heavy iron-core design	[60]

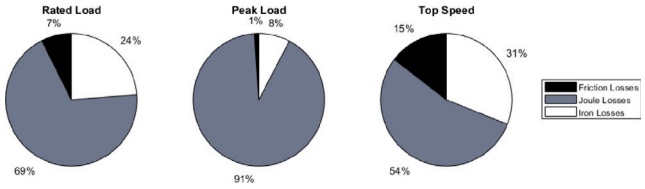

Fig. 3. Loss distribution of a PMSM for different working conditions based on [51].

to provide an external cooling flow. This enables to achieve HTCs up to 250 W/(m^2 K) [63]. These additional components increase the parasitic power consumption and also the weight of the system but active air-cooled systems provide better thermal management for electric motors.

Stator air cooling. for electric motors usually involves cooling of the outer housing/ casing surface where generally extended surfaces (passive cooling) are present to enhance the heat transfer. In order to get a better heat management in a motor, fans (active cooling) are used to circulate air in the stator interior parts such as the windings and end-windings so as to have a better cooling effect on the motor as a whole. Impingement cooling by forcing an air flow directly to the stator end windings which flows through the stator and then to the opposite coil end is another promising technique for cooling stator end windings so as to reduce temperatures in the motor hot spots. Air impingement provides high HTCs over the surface but the space and weight limitations makes it difficult to integrate it in various aviation motors [64].

Rotor air cooling. is primarily achieved by ventilation cooling such that the flow of air coming from the motor housing is guided directly into the rotor iron via certain slots or internal passages, fans are usually employed to draw in air over the rotor's surface. Alternatively, air flow can also be guided to flow over the rotor surface and carry away heat. Lastly, developing an internal finned structure on the hollow shaft that guides the air flow directly inside the rotor has also been established to provide good thermal performance in electric motors [64].

3.2.2. Liquid-cooled

HEP aviation requires electrical machines to deliver high power and energy for propulsion, the heat loads thus generated in an electric motors of high-power dense applications (≥ 100 kW) would produce high heat loads and air-cooled systems are not always suitable for the same. Liquid cooling involves circulation of a coolant throughout motor's heat generating parts in a loop (open/ closed) and then bringing this heat to a suitable heat exchanger. Liquid-cooled systems can effectively reduce the generation of high heat zones, improve heat transfer efficiency and maintain stable operating temperatures in the motor. It is worthwhile to note that these systems are usually quite complex to integrate in a motor and the addition of auxiliary equipment adds another level of complexity, weight complications and increased costs to the system. However, a trade-off between effectiveness and complexity for HEP or MEA motor cooling always depends on its applications.

Stator liquid cooling. for electric motors in general is mainly through cooling jackets where spiral or U-shaped shaped channels combined in the form of a jacket are wound around the stator and the coolant (water, water ethylene glycol, oil) which enters the motor through the inlet, carries away heat from the stationary motor parts and then exits

via outlet. Cooling jacket approach for HEP motor cooling has been under significant research but high pressure drop, increased weight and leakage losses have to be considered along with it [57]. Stator cooling can also be performed by integrating axial flow channels running directly throughout the motor stator that carry heat from the stationary parts [65]. Flooding and semi-flooding of the stator with a di-electric liquid such as oil and separating the rotatory and stationary motor parts is another effective direct liquid cooling method but involves high complexity, costs and prone to safety hazards due to leakages. A suitable and more effective way to bring the stator temperature down would be to directly cool the windings and end windings by flooded cooling, using embedded cooling channels or spray cooling [66]. HTCs of up to 100 $kW/(m^2\ K)$ can be achieved with evaporative cooling [63].

Rotor liquid cooling. In applications with high electrical power and high rotational speeds, the rotor represents a thermal bottleneck, resulting in the creation of local high-temperature zones. In such cases, high HTCs are required, typically achieved by liquid cooling. A common rotor liquid cooling design is a hollow rotor shaft in which water ethylene glycol or oil is used for heat rejection [67]. As speed increases (and thus rotor losses become greater), the cooling performance of this concept generally increases too. This is due to a secondary flow, caused by Coriolis force, and associated better mixing processes in the rotor. Similarly, installing nozzles at the end flange using impingement can cool the rotor iron and achieve high HTC [53]. Although rotor cooling techniques are important for multiple future applications, the technical implementation and integration with stator cooling options is very challenging, so intensive research is still needed [66].

3.2.3. Phase change materials

PCMs have excellent thermal storage capability, which can lead to the extension of the operating range of electrical machines, especially during transient operations. In electric motors, the use of this method has been investigated in both the stator and the rotor. Cavities in the housing or in the rotor iron are filled with paraffin or other custom materials. When heated at temperatures of about 81 °C, phase transition occurs and latent heat of about 250 kJ/kg is absorbed [68]. The absolute amount of heat absorbed, and therefore the real contribution to the transient response, depends on the amount used. PCMs are typically combined with other cooling techniques such as cooling fins in the housing (stator air cooling) or cooling channels in the stator (stator liquid cooling), since they are passive and cannot be controlled [68,69]. Another way is to integrate PCM into hollow conductors (stator windings) but this requires a great manufacturing effort [70].

3.3. Emerging technologies

The successful implementation of electrical machines in HEP requires an increase in the maximum power and power density in electrical machines. For the regional range, power outputs of 0.3–1 MW for motors and 1–3 MW for generators are expected. In the short- or medium-range range, outputs of 1–5 MW for motors and 5–10 MW for generators are predicted [71]. Scaling of conventional machines to larger outputs can be done by increasing speed, electrical load (current) or motor size. The first will increase complexity with respect to required reduction gearboxes, the second will reduce efficiency due to current-driven losses, and the last will increase machine volume and therefore weight [72]. The simultaneous increase in power density to approximately 15 kW/kg for motors and 17 kW/kg for generators by 2035 is impeded or impossible using conventional design and cooling approaches, so new solutions are being explored [73].

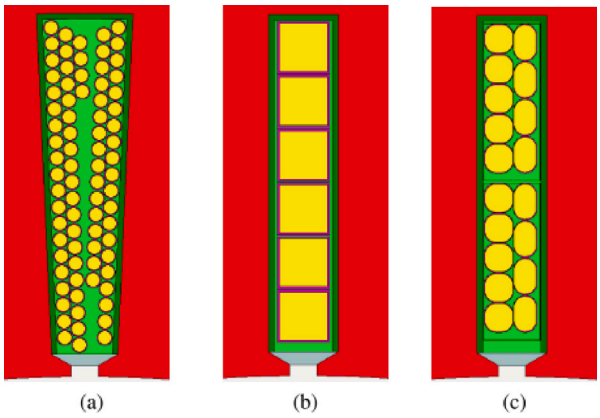

Fig. 4. Comparison of Pull-In Winding (a), Hairpin-Winding (b) and Formed Litz Wire (c) [76].

3.3.1. Litz wire

One way to minimize current-related losses in conductors is to use profiled litz wires. Litz wires aim to reduce the skin effect and proximity effect. At high currents and frequencies, currents tend to flow mainly at the surface. This results in increased electrical resistance thus in energy loss since not the entire cross-section is used. By introducing litz wires, the effective surface area of the conductor is increased and this effect can be minimized. Appropriate twisting or interweaving can reduce further the mutual influence of current displacement in the parallel conductors. This effect is called proximity effect. Through the selective use of litz wires, power densities of 17 kW/kg can be achieved even with air-cooled machines [74]. High thermal resistances, which usually occur in the slot liners, can thus be transferred to other controllable locations [72].

To enable these benefits litz wire diameters of 0.05–0.5 mm are required. They have to fulfill various electromagnetic and mechanical boundary conditions during their manufacture. Among these are the influence of the inverter on the operating frequency, the motor operating temperature or the allowable bending radii and stiffnesses [75]. Analytical models on single strand, sub-bundle and bundle level are necessary for this and increase the design effort. Manufacturing steps are often kept under disclosure. To achieve similar fill factors of +50% and thus performance increases, other developments therefore rely on hairpin windings. Although these are superior to conventional pull-in windings, they cannot achieve the efficiencies of formed litz wires [76]. A comparison of different winding cross-section and their distribution in the slot is shown in Fig. 4.

3.3.2. Cryogenic applications

The introduction of cryogenic technology is a promising step towards increasing efficiency and power densities in machines [77,78]. This is mainly due to the reduction of current-related losses and associated efficiency losses at very low temperatures. Especially for MW machines, the inefficiency of machines can be reduced to $1.3 \cdot 10^{-5}$ – $5 \cdot 10^{-4}$ [79], enabling power densities of up to 50 kW/kg to be achieved [80]. Cryocoolers are used to provide these low temperatures. Their specific mass is currently 4 kg/kW and must be reduced by at least 25% for aerospace applications [79]. The Center for High-Efficiency Electrical Technologies (CHEETA) intends to develop a machine cooled with liquid hydrogen by 2050 [81]. Other projects such as STARC-ABL are relying on Separately Excited Synchronous Motors whose rotors are superconducting and shafts embed the cryocooler [82]. Also, the introduction of ultra-pure aluminum instead of copper can significantly increase the power density in the cryogenic application [83]. However, for aerospace purposes, the safety of these new technologies must first be evaluated. The current low reliability

of the cooling components involved (pumps, cryocoolers, valves, heat exchangers), along with the potential flammability of cryogens (hydrogen) and possible unintended condensation of vaporized fluids pose safety risks that must be mastered [79].

4. Heat exchangers

Management of waste heat of individual components is crucial for the effective functioning of (hybrid)-electric aircrafts. There are several TMS elements that generate high heat fluxes and require a suitable heat exchanger design for effective dissipation of this heat [84]. Currently, conventional HEX concepts, such as compact car-radiator style HEXs, are being employed in hybrid-electric aviation, but new HEX concepts such as additively-manufactured HEXs, heat pipes, porous media HEXs, etc. are becoming more commonplace [85].

4.1. Applications in aviation

There are three main areas where HEXs are used in an aircraft which include the propulsion cycle, Environmental Control System (ECS) and the TMS. Furthermore, the construction type of the HEX used depends on the purpose and the boundary conditions of operation. Some boundary conditions of operation include fluid inlet temperatures, flow rate, fluid inlet pressure, inlet effect, symmetry condition of the HEX model, no-slip condition, etc. Depending on the particular use case, these boundary conditions would dictate the construction type of the HEX, like, for example, if the temperatures are high then metal HEXs, like HEXs made out of titanium or stainless steel, or aluminum are used, otherwise plastic or ceramic HEXs are preferred for colder temperatures; if the flow rate is high, then smoother HEXs are preferred and for lower flow rates, a rough HEX is usable, etc. HEXs used in the TMS of hybrid-electric aircrafts and in the heat management of TMS elements will be the primary focus of this section, although with suitable modifications they can be adapted to satisfy the structural constraints and the heat transfer requirements pertaining to ECS and propulsion systems [86].

4.1.1. Heat exchangers in the TMS

Different TMS elements of a HEP system have different operational conditions and cooling requirements. To satisfy the thermal management of the TMS loop, we could have a design with one HEX serving as a hub of heat transfer or there could be a design with HEXs for each TMS element based on individual requirements.

Designs with one HEX serving as a hub of heat transfer for overall cooling are currently popular because the design is more simplistic. Here, only a single HEX is to be designed, commonly a car-radiator style compact air-cooled HEX and is located at a region of the aircraft convenient for air intake (namely the scoop or the nacelle). The main disadvantage of this design is the requirement of an extensive piping network for coolant transportation from TMS elements distributed through the aircraft. Furthermore, a critical failure in the main HEX would result in an inability to cool all the TMS elements, therefore leading to an overall aircraft-level catastrophic failure.

Design with HEXs for each TMS element based on individual requirements would be a solution to mitigate the above-indicated disadvantage. Spatial distribution of HEX will mitigate an aircraft-level catastrophic failure, reduce the piping system, allowing for a better HEX design tailored to individual TMS element requirements, etc. This design style is advantageous in the context of emerging technologies such as additively-manufactured HEXs, heat pipes and metal-foam integrated HEXs, allowing for more innovation in designs. The main disadvantage of this design would be the choice of location and possible weight increase, as locations for air-cooled HEXs are limited and the aerodynamic design of the aircraft should not be distorted [87].

4.2. Heat exchanger classification

Heat exchangers categorization is based on numerous classification schemes including, heat transfer processes (direct or indirect), number of fluids, fluid phase, construction type, compactness, etc [84,86,88]. These are illustrated in Table 3. The table illustrates the fundamentals of HEX classification based on the above criteria. For a HEP system design, some of these criteria adhere to conventional design choices, with the heat transfer process being indirect, the number of fluids usually two and the fluid phases being a two-phase (air-coolant) or a one-phase (liquid-coolant). Some other criteria, like HEX construction type and compactness, do not adhere to conventional design criteria, mainly owing to the limited space for HEXs available in HEP systems. Surface compactness describes how much heat transfer surface area a heat exchanger utilizes per unit of its overall volume. The construction type refers to the overall geometry of the HEX. For HEP systems, the HEX compactness is high and the construction type is non-conventional, innovative and the geometry is modified to accommodate high HEX compactness.

4.3. Heat exchanger requirements

There are some overarching requirements that HEXs in aviation are expected to tackle. These mainly include weight, effectiveness, costs, safety and certification. For a HEX to actually be used in an application context, the requirements that assume priority are weight, costs and certification, followed by effectiveness. However, for HEP aircraft, it is to be noted that the emphasis is to prove HEP aviation via demonstration, which would require prioritization of weight, basic safety and effectiveness over costs. Costs and certification would become of interest when the design is at a higher TRL. However, it is to be noted that all requirement criteria are important, but the assessment of relative importance is crucial towards prioritizing certain criteria at different TRLs.

4.4. Emerging technologies in heat exchanger design

There are new emerging technologies in HEX design in order to achieve better heat transfer. One such method which is being investigated is the integration of HEXs into preexisting structural components. This method allows for effective usage of aircraft space, and weight reduction, while still achieving heat transfer, e.g. surface heat exchangers [98]. While such designs are still at a lower TRL, they are being heavily researched [99]. Among all, Anibal et al. [100] demonstrated the shape optimization of surface heat exchangers for X-57 Maxwell aircraft motors using a conjugate heat transfer model. The methodology can also be applied to optimize additively manufactured coolers [101,102], which is introduced hereafter.

4.4.1. Additively manufactured heat exchangers

Additively manufacturing has a major impact on the design of HEXs as it allows for greater design flexibility. Additively manufactured HEXs satisfy the requirements of weight and effectiveness. By introducing manufacturing techniques like SLM or XX light-weight design with high compactness and complex geometries can be achieved. However, they poorly satisfy the requirements of cost and safety. The manufacturing techniques, post-processing techniques, and equipment are expensive. The manufacturing materials include metal powder, like AlSi10Mg or SS316 powder, or ceramics, and plastics, which are costly. Safety concerns or certification for aircraft application is premature because the technology is at a lower TRL (TRL 4–5), which would indicate successful tests in a laboratory setting but a lack of tests in a real-world application. Nevertheless, it is to be noted that higher heat dissipation requirements for HEP systems can be met by these HEXs, and therefore they are rigorously researched. [85,103,104].

Table 3
Classification of heat exchangers.

Primary classification	Secondary classification	Tertiary classification	Features and examples	Reference
Heat transfer process	1. Direct contact: Heat transfer through direct fluid contact 2. Indirect contact: Physical barrier exists between the fluids. Further classified into Recuperators and Regenerators.	2.1 Recuperators. 2.2 Regenerators.	2.1 Involves continuous heat transfer between two fluids and requires a simultaneous flow of two or more fluids. 2.2 Involves intermediate storage of thermal energy in the core of a heat exchanger (termed as the matrix).	[89–93]
Number of fluids	1. Two fluids 2. Three fluids 3. More fluids	1.1 Air–liquid HEX. 1.2 Liquid–Liquid HEX.	1.1 involves heat transfer between the air and coolant fluid, e.g, car radiator. 1.2 involves heat transfer between two liquids, e.g, shell-and-tube HEX 2.1 E.g., Cross-flow three fluid HEX in refrigeration systems and chemical processing 3.1 E.g., Four-way Cross-flow HEX in industry.	[84,86]
Fluid phase	1. Single-phase fluids 2. Two-phase fluids.	1.1 Liquid–liquid HEX. 1.2 Gas–gas HEX. 2.1 Gas–liquid. 2.2 Solid–liquid.	1.1 E.g., shell-and-tube HEX 1.2 E.g., Engine air pre-heaters, cabin air heaters. 2.1 E.g., car radiator 2.2 E.g., Heat sinks used for cooling of power electronics.	[86,94]
Construction type	1 Tubular 2 Plate-type	1.1, 2.1 Moving parts or fixed 1.2, 2.2 Primary heat surfaces or extended surfaces 1.3, 2.3 Single-pass, cross-flow, parallel-flow or counter-flow 1.4, 2.4 Multi-pass	1. Uses tubular structures for achieving heat transfer. Mainly used in heavy industry applications but designs have also been adapted for usage in aircraft HEX involving heavy piping. 2. Involve plates and flat surfaces for achieving heat transfer.	[63,95,96]
Compactness	1. Compact heat exchanger 2. Non-compact heat exchanger	–	1. Heat transfer surface area to volume ratio over $700m2/m3$ for a gas-to-liquid HEX or over $400m2/m3$ for a liquid-to-liquid (or phase-changing) HEX. 2. Heat transfer surface area to volume ratio under $700m2/m3$ for a gas-to-liquid HEX or under $400m2/m3$ for a liquid-to-liquid (or phase-changing) HEX.	[87,97]

4.4.2. Heat pipes

Heat pipes mainly allow for heat transfer via capillary action, and although conventional use in aviation has been limited, they are becoming more prominent. They satisfy the requirements of weight and effectiveness. They are small, light and have an excellent heat transfer ability. In traditional aircraft, heat pipes have been used in the engine for heat removal from the combustion chamber or turbine, from electronics such as radars or navigation systems, from the brakes of the landing gear, from particularly hot sections of the aircraft skin, etc. Heat pipes would be at a TRL 6–7 because they have been demonstrated in a relevant environment. However their potential for application in the aviation sector is much higher and with further development, they can be more widely used after appropriate safety or certification criteria for aviation applications. The intricacy of the design and a larger variation from a conventional design would make them costlier and would require more time and effort to achieve the final part [105].

4.4.3. Porous media integrated heat exchangers

As an extension of additively manufactured heat exchangers, porous media-integrated heat exchangers are coming into significance in the field of aerospace engineering. They satisfy the requirements of effectiveness, whereas perform poorly with costs and safety. Porous media, by virtue of their enormous surface area, allow for a significant heat transfer. However, with an increased surface area, comes certain challenges, including increased pressure drop or less structural integrity. Nevertheless, they have a high potential to play a significant role in the aviation industry [106–109]. An example of a porous media integrated heat exchanger is a metal foam HEX, which has metal foam integrated into it, and has proven to have excellent heat transfer behavior in comparison to conventional heat exchangers [110].

5. Batteries

In order to transit smoothly from conventional propulsion systems like jet engines to renewable fuels the aviation industry needs to overcome a massive hurdle which is the energy density of the storage methods. Compared to kerosene which fuel jet airliners currently use, the energy density of the most popular lithium-ion batteries (LIBs) currently available in the market is outperformed by a ratio of nearly 40:1. This means to power a conventional aircraft with batteries, the battery weight required for propulsion would be 40 times more. Fully electrified aviation is still a long way in the future, the presence of HEP technology can significantly reduce high electric power demand and hence an improvement of the energy storage system (ESS) [111].

LIBs have been a major contributor of electrical energy in various industries. Good power density, low weight, high reliability, and a steep

learning curve are some key indicators of LIBs flexibility of operation [112]. It is thus evident why LIBs have dominated the electronics and energy market for such a long time. At the same time, the thermal and parasitic-related reaction losses limit the performance of batteries in hybrid-electric aviation. Heat generation in a battery cell is the result of the cell kinetics, species transport, and ohmic losses. Heat generation of a battery model can therefore be represented by Eq. (5) [113].

$$q = I(U - V) - I\left(T\frac{\partial U}{\partial t}\right) \tag{5}$$

Here, the first term on the right side describes the electric power, the second term is the reversible heat and U represents the open circuit voltage. Eventually, heat generation of LIBs via side reactions under high temperatures and voltage can be collectively described by Q_s and this contributes to roughly 20%–30% of heat generation in a battery while the major part being ohmic heat (50%–60%). The electric power is represented by ohmic heat and hence heat generation equation can then be expressed as Eq. (6) [113].

$$q = I^2R - I\left(T\frac{\partial U}{\partial T}\right) + Q_s \tag{6}$$

5.1. Battery thermal challenges

Batteries have a very restricted thermal boundary (15 °C–35 °C) for optimum operation beyond and under which the thermal characteristics of a battery system may significantly change and deteriorate its performance, life, and safety (see Figs. 5 and 6). Understanding these thermal conditions for batteries is relevant to explaining the thermal losses in a battery and also for the design of an efficient cooling method.

Most of the temperature-related effects in a battery are the result of battery materials and chemical reactions associated with it. The chemical rate of reaction and reaction temperature are directly linked such that any temperature variation would lead to a change in battery electrochemistry [114]. At lower temperatures, battery's internal resistance increases and the chemical reaction rate slows down which leads to a loss in battery efficiency and its storage capacity [115]. Charge-transfer resistance of LIBs at lower temperatures increases such that it is much more challenging to charge a battery at a low temperature than discharging it. Additionally, slow diffusion of lithium ions within the electrodes occurs at low temperatures which causes performance degradation [114]. The process of self-discharge is also accelerated at lower temperatures thus reducing the overall energy available from the battery. Exposure to a cold environment can also give rise to cell damage wherein the internal components of a battery could be severely damaged and also the electrolyte in a battery may freeze.

As more and more energy-dense batteries are being produced, the electrode materials tend to get highly reactive which causes thermal implications at elevated temperatures. These implications can cause anomalies in the thermal reactions of a battery cell which leads to thermal runaway [116]. This uncontrolled heat generation at the cell level may cascade into a chain of reactions with increasing temperatures and lead to an explosion. It is therefore much evident to have an efficient TMS that controls and mitigates excess heat in the batteries efficiently. Heat generation during charging and discharging, exposure to external heat, and internal short circuits are some of the major initiators of temperature rise in batteries. Capacity loss and impedance increase due to the modification of the solid-electrolyte interface layer is another effect of elevated battery temperatures [117].

Uniform temperature distribution in a battery at the cell, as well as module level, is essential for safe operation. Development of localized hotspots can occur with uneven temperature gradients that can limit battery's performance, cause thermal capacity degradation, and propagate differential and untimely battery aging. A key indicator of an efficient battery pack design is a 5 °C limit in the uniformity of module temperature [118].

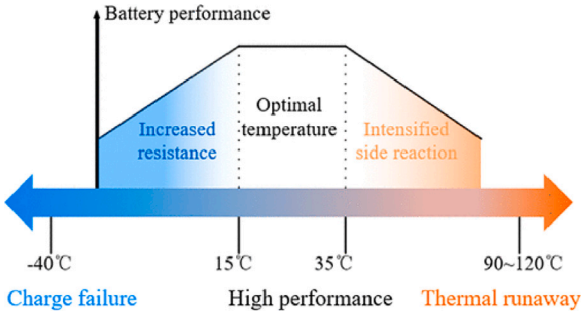

Fig. 5. Temperature range for optimal battery performance [119].

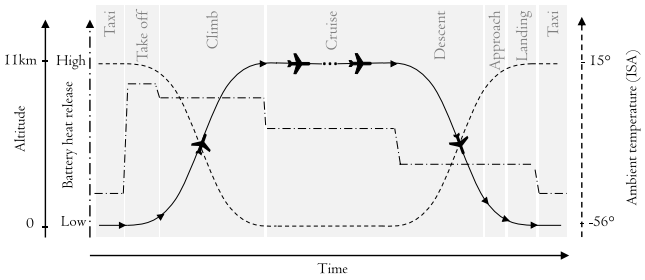

Fig. 6. A typical battery heat release over a HEP flight cycle.

5.2. Battery thermal management

A critical aspect of hybrid electric aircraft design is to enable safe and optimum operation of the battery pack. In order to achieve that, an efficient battery thermal management system (BTMS) needs to be employed in the aircraft. As discussed in the previous section, temperature variations in a battery cell can have adverse effects on the performance of the battery module and then propagate to the ESS as well therefore the basic aim of a BTMS would be to maintain the most favorable temperature range for the battery operation [118]. Besides maintaining a uniform temperature of the battery pack, BTMS is also utilized in temperature monitoring and control, providing pre-heating to the battery in colder conditions and providing thermal insulation between the environment and adjacent components of the TMS.

5.3. BTMS classification

TMS for battery systems can be classified based on their operating principle, components, and architecture. The most common classification of BTMS can be done as follows:

5.3.1. Air-cooled

The simplicity of design and low cost make air-based BTMS an attractive prospect for battery thermal management. The idea is to utilize the airflow in order to dissipate heat from the battery pack. Owing to low heat transfer coefficients, air-cooled systems are usually coupled with enhanced structures such as fins and extended surfaces on the module casing which increases the heat transfer behavior and makes it more effective. The simplest approach to cool down the battery pack would be to directly impinge air onto the battery cells but this might need additional equipment and filters to protect the battery pack from damage by external objects and hence added weight and complexity [120]. Perullo et al. [121] proposed the utilization of excess air from ECS to cool the ESS unit of a 76-passenger MEA regional jet and limiting the pack temperature to 45 °C. Nevertheless, ram air cooling can be achieved during flight to direct external airflow directly to heat exchangers but this approach pertains to a system-level TMS rather than BTMS itself [32]. Although air-cooled battery

systems provide significant benefits in terms of simplicity, weight, easy maintenance, and reduced complexity for commercial electric vehicles (EVs), high-power demand, inability to maintain temperature uniformity, and reduced cooling efficiency limit its practical applications for HEP aviation so far [122].

5.3.2. Liquid-cooled

Liquid-based BTMS offer high efficiency and high cooling capacities when compared to the air-cooled system [119]. A large amount of heat can be transported using liquid-cooled battery systems owing to the high heat transfer coefficients and high thermal conductivity. The high density of the liquid makes it easier for the architecture design such that the transportation lines are smaller [32]. For liquid cooling systems to operate effectively, they must consider potential safety issues such as leakage losses from pump operations, fluid contamination, and the risk of fire hazards that can arise during the flow of coolant through pipes. The maintenance cost, complexity, and weight of liquid-cooled systems are hence increased but the capabilities of managing high heat loads and ensuring uniform temperature distribution between the cell units make it still a widely used ESS cooling technique [34,123].

Mode of contact between the working fluid/ coolant and the battery sub-divides the liquid cooling BTMS into direct and indirect cooling. Batteries are directly immersed in a dielectric fluid in the former case whereas heat dissipation in the latter case is by virtue of certain channels or cooling plates around the battery cell or module. Active cooling using liquid-cooled plates for a hybrid electric aircraft has been presented in the works of Hoenicke et al. [124] and Rheaume et al. [34]. Liquid cooling by comparing water, ethylene glycol and Fe_2O_3 nanofluids as coolants for HEP aviation LIBs has also been studied [125]. Annapragada et al. [123] analyzed the potential of using wavy channel cooling (cylindrical cells) inspired by Tesla's patent design [126] for a 1780 kWhr HEP battery system. This study resulted in providing an effective thermal solution for an aviation battery but at the same time weight of the heat acquisition system was found to be nearly half as that of the battery cells themselves hence leading to a heavy BTMS.

5.3.3. Phase change materials

Phase change materials (PCM) have the ability to undergo phase transition i.e. from solid to fluid or vice versa and store high amount of heat while maintaining constant temperatures because of their high latent heat capacity. High latent heat of the PCM allows it to absorb a significant amount of heat or cold energy without substantial temperature changes, which implies it can act as a great thermal storage device [13]. Thermal conductivity of PCMs is relatively low therefore they are sometimes filled in with certain metallic materials to overcome the inherent material defects [119]. Commonly used PCMs are paraffin, graphitized carbon, sodium acetate, and water. Key features that make PCM a popular choice for HEP BTMS would be [32]:

- Defined temperature range for material phase change.
- Thermal buffering to control temperature fluctuations during transient events.
- Thermophysical properties for solid and liquid phase is different.
- Chemically stable, non-corrosive, and non-flammable.
- Low cost, low complexity, long cycle life safe, and simple design.
- Integration with other BTMS e.g. air-cooled system.

PCMs are passive systems that lack operational flexibility, they need to be contained in an ambient atmosphere before take-off so that they do not acquire additional heat and also there needs to a residence time for PCM cooling after being charged again [120]. Also, the cooling capacity of the PCM gradually decreases with its melting process. In the case when PCM is completely melted, thermal barrier between the battery and external environment would increase and create thermal hindrances. Numerical and experimental investigations for the use of PCM in battery cooling have been conducted extensively in the past for EVs while showing promising results [118,119]. PCM as a method for heat dissipation in aircraft ESS units has already been into consideration and patented [127,128]. Chen et al. [129] investigated the use of PCM and finned structures in cylindrical cell BTMS for application in aerospace industries. Research activities conducted in the past show the capabilities of PCM being used in aircraft BTMS extensively but particularly for HEP BTMS, the topic is still a matter of research [13,16,32,130].

5.4. Emerging BTMS technologies

Iterations on improving thermal management of batteries are never-ending and with the increase in battery energy density and power density with higher heat loads, it makes much sense to explore the possibility of advanced cooling techniques for BTMS in the light of HEP aviation.

5.4.1. Thermoelectric cooling

Thermoelectric cooling (TEC) utilizes the concept of the Peltier effect in order to actively transfer heat. On the application of voltage at one end of the Peltier element, heat is pumped to the other side. Alternatively, the Seebeck effect explains the generation of electric potential due to an existing temperature gradient. The temperature difference between the hot and the cold ends is governed by the potential difference across the conductor. The pumping of heat from one end to the other can provide a cooling effect as well aid the battery in times of pre-heating [32]. Kellermann et al. [120] designed and analyzed a TEC BTMS for a 19-seater hybrid electric aircraft. Limitations to the coefficient of performance value for TEC is a major drawback of this technology but it provides a better temperature control of the ESS since each Peltier element can be controlled. Additionally, TEC cooling is a robust, low maintenance cost, compact, and reliable technology with the possibility of providing cooling below ambient temperature but the primary concern of low efficiency and high energy consumption makes it less effective than other BTMS technologies [122].

5.4.2. Cryogenic cooling

An active area of current research is the implementation of cryogenic cooling of batteries for HEP architecture. The basic principle is to expose the batteries to cryogenic fluids like liquid nitrogen or liquid hydrogen under extremely low temperatures (< 70K) such that heat is transferred rapidly from source to fluid [32]. Cryogenic systems although highly efficient, still require a lot of auxiliary equipment, safety measures, and coolant management which in turn increases the system weight, cost, and complexity significantly. Ravikovich et al. [131] provided a thorough analysis of the implementation of cryogenic cooling based on the reverse Brayton cycle that could act as an effective BTMS and also cool the other electric power components. A direct transfer to cryogenic cooling with the current HEP architecture would require significant research in the sector but can provide great thermal management potential. ENABLEH2 (ENABLing cryogEnic Hydrogen based CO2 free air transport) a joint EU project on the investigation of cryogenic cooling for civil aircraft paved the way for understanding thermal management of aircraft components using liquid hydrogen [132]. Another EU project (EFACA) currently running until 2026 will focus on the scope of cooling using liquid hydrogen fuel [133].

6. Power electronics

6.1. Types of power electronics

Power electronics (PE) serve to convert and alter power between different alternating current (AC) and direct current (DC) loads as efficiently as possible. Power electronic systems connect loads and sources in electrical systems that are incompatible with each other. Depending on the type of conversion, a distinction is made between:

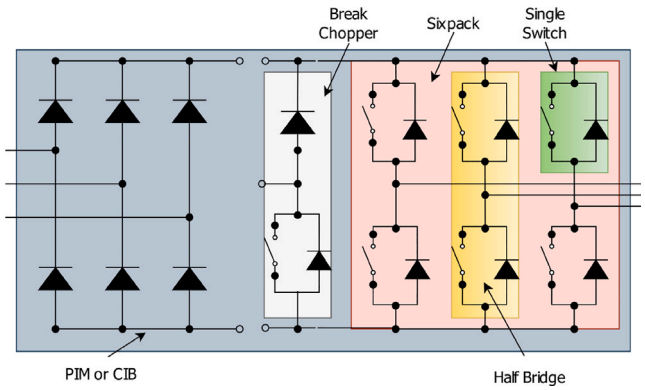

Fig. 7. Semiconductors grouped in power modules [135].

- AC–AC: Transformer,
- DC–DC: Boost, buck or buck–boost converter,
- AC–DC: Rectifier and
- DC–AC: Inverter.

The conversion takes place by means of semiconductor devices that act as switches. They can be divided into uncontrolled (diodes) and controlled (e.g. MOSFET, IGBT) devices. The efficiency and quality of the conversion depend on the materials used (e.g. silicon-based, silicon carbide, or gallium nitride), the architecture/topology (e.g. 2-level, 3-level), the control (space vector or sinusoidal pulse width modulation) and the power quality (active and passive power filters). Based on the HEP architecture, different power converters are applied at different locations in the aircraft. For example, inverters are used for motor control of PMSM, rectifiers are used after the generator in turboelectric propulsion concepts, boost converters are used to step up the DC voltage from the possible fuel cell level to the required system level, or transformers are used in the communication system.

6.2. Power modules

A power module is an assembly of discrete semiconductor devices or a combination of multiple power electronics components interconnected to perform different power conversion operations [134]. Depending upon the application, power modules are arranged in different architectures that include gate drivers, semiconductor devices (e.g. Diode, MOSFET, IGBT), passive elements (e.g. resistor, capacitor, inductor) and sensors. Power modules can minimize undesired side effects of the individual discrete components by selective arrangement. Typical configurations are:

- Single switch (IGBT and freewheeling diode),
- Half-bridge (1 phase inverter consisting of two single switches),
- Six-pack or full bridge (3-phase inverter consisting of 3 half bridges),
- Break chopper (diode/IGBT with freewheeling diode) and
- Power integrated modules or converter inverter break (rectifier, break chopper, 3 phase inverter).

A topological explanation can be seen in Fig. 7.

It is necessary from a thermal, electrical and mechanical point of view for the modules to be constructed to suit high-power applications. Irrespective of the topology, power modules are an integration of semiconductor chips, solder, substrate, wire bonds, baseplate, grease, terminals and a housing as depicted in Fig. 8. Heat generated in the chip is conducted through each layer and finally to the baseplate which is further connected to a heat sink, cold plate or some other cooling system where heat dissipation occurs.

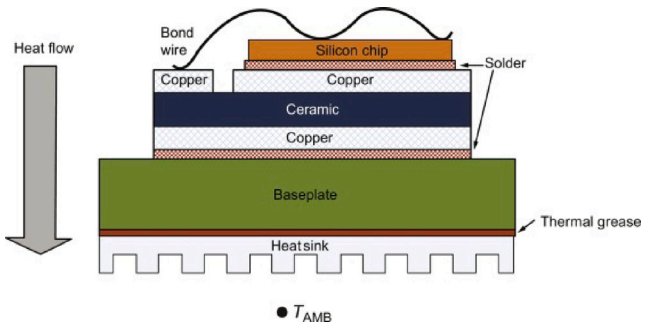

Fig. 8. Cross-section of a power module with heat flow [134].

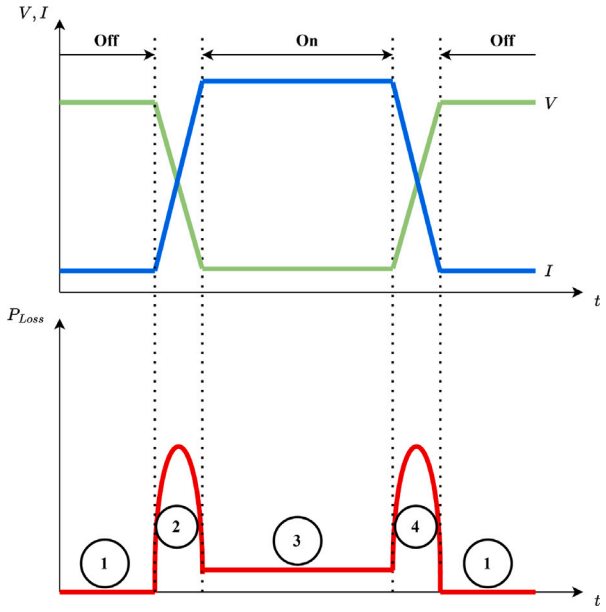

Fig. 9. Losses in Power Electronics: ① Blocking Losses, ② Turn-On Losses, ③ On-State Losses and ④ Turn-off Losses.

6.3. Losses

Various losses occur during the operation of power electronics. These can be divided into static and dynamic losses. Static losses $P_{L,stat}$ occur during the on-state as well as during the off-state of the switch and are also referred to as blocking losses ① and conducting losses ③. Dynamic losses $P_{L,dyn}$ occur during the switching between on-state and off-state. These are referred to as turn-on losses ② and turn-off losses ④. A simplified representation of losses ①–④ is shown in Fig. 9. From this, it can be seen that dynamic losses are proportional to frequency f_{sw}, while static losses are proportional to current (I). The bipolar nature of an IGBT makes it the preferred choice in high current applications, since the static losses according to Eq. (7) only increase linearly. In contrast, static losses in MOSFETs grow quadratically with increasing current, see Eq. (8). However, the characteristics E_{on} and E_{off} are different between switching devices making the MOSFET the better choice for the same current rating, see Eq. (9) [135].

$$P_{L,stat,IGBT} = I \cdot U \tag{7}$$

$$P_{L,stat;MOSFET} = I^2 \cdot R \tag{8}$$

$$P_{L,dyn} = (E_{on} + E_{off}) \cdot f_{sw} \tag{9}$$

6.4. Cooling

Power electronics components i.e. switching elements and passive devices incur losses while operating and generate heat. Effective cooling of these semiconductor devices is essential in order for them to operate under safe temperature limits.

6.4.1. Air-cooled

Air cooling in PE modules is usually done via finned heat sinks attached to the baseplate. Depending on the heat load, convective heat transfer in air-cooled systems can either be natural (passive) or forced (active). When power dissipation numbers exceed 100 W/cm^2, air-cooling does not usually fulfill the cooling requirements [134].

A three-phase medium-voltage SiC inverter (MW-scale) for electric aircraft propulsion with air cooling of H-bridge modules was developed and presented in the works of Diao et al. [136]. The inverter developed provided a lightweight PE converter with reduced switching losses, increased power efficiency, cost-effective and high-reliability solution. Modeer et al. [137] designed a double-sided modular approach of a forced-air cooling inverter system with an aluminum heat sink for electric aviation. The research led to an improved, efficient, lightweight and highly power-dense inverter design but generated certain voltage-dependent dynamic losses. Simulation results from an air-cooled TMS for NASA's X-57 aircraft with the airflow from the motor to adapt to inverter cooling have been presented in the works of Batteh et al. [138].

6.4.2. Liquid-cooled

Liquid-cooled power modules most commonly involve a cold plate that is thermally connected to the baseplate such that the coolant flowing through the cold plate carries away the heat. Alternatively, direct liquid cooling using spray, immersion, and micro-channels is also possible to be integrated in the module design [139]. Liquid cooling systems provide high thermal efficiency, high heat load capacity, compact design and quiet operation. At the same time, liquid cooling can be complex, heavyweight, costly, and cause leakage losses.

TMS architecture to cool the motors and inverters together such that heat load from the inverter is dumped into a cooling oil which in turn runs through an air–oil heat exchanger is described by Shi et al. [45]. The authors revealed that the TMS cannot cool the PE efficiently during peak loads therefore, an option to use additional coolant to take up peak heat loads or use PCM to absorb excess heat was proposed. The improved TMS design in both cases was able to contain heat from the inverter but added penalties in weight and fuel burn during take-off. McCluskey et al. [57] proposed an integrative PE and motor cooling design for a 200 kW and 1 MW hybrid electric aircraft. The first design considered mounting of PE modules on the cooling jacket so as to cool the PE and the electrical machine simultaneously with minimal pumping requirements. This design is compact, lightweight and energy efficient but can induce significant vibrations. Another approach discussed in this work was to place the PE with a dedicated circumferential cold plate around the surface just before the motor such that the cooling loop would first cool the PE and then the motor. This approach prevents mechanical and thermal interactions between the motor and PE but adds up to the system weight. Mounting of components on a cold plate for the liquid cooling system in MEA has been investigated in the works of Pal & Severson [140]. They also discussed effective PE thermal management via liquid cooling considering weight penalty alongside various other PE heat acquisition and rejection paths at the aircraft level.

6.5. Emerging technologies

6.5.1. Wide-bandgap semiconductors

Efficient, reliable, cost and weight-effective PE is the current demand for HEP aviation. Traditional semiconductor devices (SiC or GaN) alone cannot fulfill the requirements of future aviation needs. Wide-bandgap (WBG) semiconductors generate large breakdown fields over a small distance, thus making PE modules smaller in size and with high switching frequencies. WBG semiconductors offer superior performance in terms of reduced conduction and switching losses, high voltage operation, high operating temperatures, resistance to radiation, and faster-switching frequencies [141]. All these features make WBG semiconductors an attractive candidate for propulsion systems in hybrid and all-electric aviation.

6.5.2. Cryogenic power electronics cooling

A promising and proliferating area of research for future hybrid and all-electric propulsion is cryogenic cooling of PE. At cryogenic temperatures many electronic components exhibit superconductivity such that they have a superior performance with minimal losses. The availability of liquid hydrogen at temperatures of nearly 22 K suits the purpose of cooling electronic components. Alternatively, liquid nitrogen, liquid helium and liquefied natural gas can also be used as cryogenic coolants [141]. Cryogenic cooling majorly aids in:

- Reducing semiconductor devices on-state resistance thereby reducing switching losses.
- Faster switching speeds and increased current densities for inductor windings.
- High efficiency and power dense systems.

Major drawbacks of cryogenic PE cooling includes increased design complexity, high system weight, cost penalty and high closed operation losses as compared to mechanical circuit breakers [141].

A 1 MW cryogenic-cooled inverter design with experimental test set-up for electric aircraft propulsion was established and tested at full load capacity using both liquid and gaseous nitrogen as a coolant in the works of Chen et al. [142]. The results provided insight into how cryogenic cooling in inverters can lead to high power dense and efficient inverters for future hybrid and all-electric flights but at the same time increase the system weight and complexity. Boll et al. [143] presented the cooling of a 10.5 MW inverter using aluminum cold plates with liquid hydrogen for a 220-passenger short-range HEP aircraft. It was found that cry-cooled inverters increase the system efficiency but at the same time carry significant weight and pose safety threats due to leakages. It is, therefore, necessary for future HEP aviation to focus on optimizing hydrogen tanks, system weight and component behavior in cryogenic temperature ranges. Barth et al. [144] also proposed cold plate cooling of a three-level 1 kW single phase power converter for hybrid electric aircraft with liquid nitrogen coolant at near-cryogenic conditions. The results showed a 16 % improvement in thermal losses under test conditions compared to cooling at room temperatures. Utilizing PE in the cryogenic system of a liquid hydrogen cooling scheme for electric aircraft can provide good protection of PE modules from the external environment and system efficiencies of 99.4% can be achieved. It was also pointed out in this research that besides weight penalties, operating inverters and converters at cryogenic temperatures is not always suitable [145]. NASA, GE, and Boeing have together developed a lightweight SiC cryogenic-cooled inverter system (MW class) for HEP aviation under the Advanced Air Transport Technology project [146]. The Polaris project aims to develop a superconducting power distribution system for turboelectric transport aircraft using liquid hydrogen [147].

An overview of different inverter topologies and their cooling strategy for various hybrid and all-electric aviation applications is presented in Table 4.

7. Pumps and fans

Pumps and fans are important components of a thermal management system in most situations. In a liquid-cooled system, the cooling medium recirculates in a closed duct system to carry the heat from the

Table 4
Inverter technologies used in electric aviation applications.

Inverter technology	Power class	Efficiency	Cooling	Features	Challenges	Reference
7-L ANPC Inverter	1 MW	98%	Forced-air	• High-power • Cost-effective • Reduced harmonics	• High conduction loss • Complex architecture	[136]
9-L FCML Inverter	6 kW	98.6%	Forced-air (double-sided modular cooling), aluminum heat sink	• Reduced commutation loop inductance • High power density	• Voltage-dependent dynamic losses • Complex architecture	[137]
3-L ANPC Inverter	1 MW	99%	Active-liquid (cold plate cooling), water as coolant	• Novel control strategy • High power density (12 kVA/kg)	• Heavyweight • Complex and costly • Surge voltage stress	[148]
3-L ANPC Inverter	1 MW	99%	Cryogenic (modular cold plate and housing design), liquid and gaseous nitrogen as coolants	• High power density (18 kVA/kg) • Good performance	• Heavyweight • Complex design • Considerable switching loss	[142]
3-L NPC Inverter	10.5 MW	99.75%	Cryogenic (aluminum cooling plate), liquid hydrogen as coolant	• Low thermal losses • High operating voltage (850 V per module)	• Very heavy design • Pumping losses • Radiation loss	[143]
FCML Single-phase Inverter	1 kW	98.2%	Cryogenic (cold plate), liquid nitrogen as coolant	• Low thermal losses	• Conduction losses	[144]
Power Inverter	1 MW	99.4%	Cryogenic cooling, liquid and gaseous hydrogen as coolants	• High effectiveness • High heat load dissipation	• High-pressure drop • High mass flow rate requirement	[145]

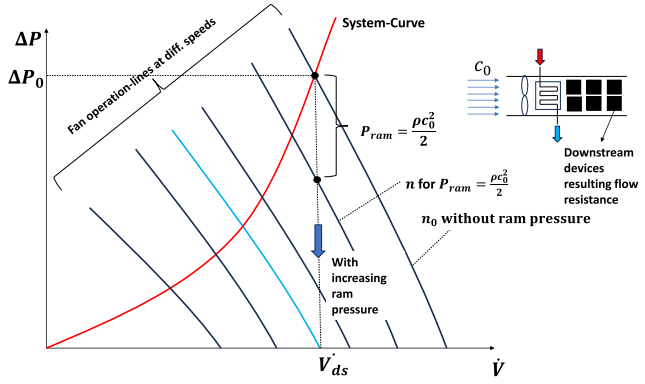

Fig. 10. Fan characteristic and its operation behavior: response of fan speed against increasing ram pressure for a certain pressure gain requirement.

hot source and release it at the heat sink, e.g. heat exchanger. The cooling medium, which, depending on the heat source temperature, might be pressurized for increasing boiling temperature (e.g. 1 bar overpressure in motor vehicles), is set in motion by a pump whose flow rate (or the corresponding pressure gradient between the supply and return sides) can be adjusted by adjusting the pump speed or pump geometry. While the liquid movement is realized by a pump, the air, in case of an air cooling or an air-cooled heat exchanger, is moved by a combination of ram pressure and fan. Both apparatuses, which belong to the turbomachinery field, can be described by a so-called turbomachinery characteristic in a similar way. As an example, the operating behavior of a fan in a duct system is explained here in terms of control, and shown in Fig. 10.

Depending on the operating condition of a vehicle (in aviation would be aircraft), or the heat to be dissipated, the required air flow rate will also be different. The total pressure gradient for a given air flow rate can be obtained directly from the system behavior. Assume that the required air volume flow $\dot{V}_{ds}$ remains constant. In this case, the fan speed must be reduced as the vehicle speed increases. For a fan with a constant blade installation angle, speed control is the only way to influence the air flow rate depending on the specification. However, for a fan with a variable blade installation angle, the airflow rate can be controlled besides speed control by adjusting the installation angle. A variable geometry fan has better controllability and a wider operating range with high efficiency compared to a constant fan [149]. However, the increased complexity may also result in higher construction costs and greater susceptibility to failures.

The fan and pump should ensure that the components are not overheated even in the worst case. For example, one of the worst cases is when the dynamic pressure does not exist and the air has to be set in motion only by the fan or propeller. A TMS should be able to identify the worst situation of the cooling system at the beginning of the development phase and determine the appropriate fan and pump accordingly. With the electrification of modern thermal management systems, the individual electric fans and pump can be effectively and highly dynamically controlled depending on the operating behavior of the propulsion system [150,151]. Besides the superior controllability of an electric pump, it can be manufactured more compact and lighter together with a high-power motor compared to a mechanical pump, which makes it more suitable for aviation applications. Some well-known pump manufacturers are for example Pierburg from Rheinmetall, Cascon, and AMETEK PDT. Fig. 11 shows some of Pierburg's products together with their characteristics. Based on the requirements of the TMS calculation, suitable products can be selected. To effectively decrease the pump size (lower flow rate/lower pressure gain) and the associated electric consumption, the coolant should be transported as short as possible and the heat transfer at different components should be as effective as possible. While the first requirement can be fulfilled by a smarter arrangement, the second challenge is strongly coupled with that of the application of advanced cooling methods in components.

8. Fuel cells

Fuel Cells (FC) are a potential technology for electric power generation in electric and hybrid electric aircraft with reduced emissions.

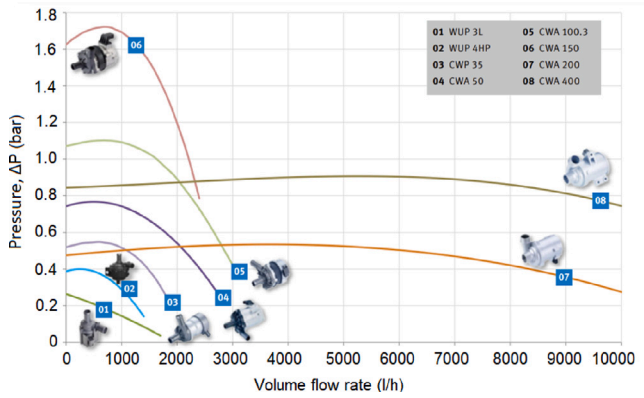

Fig. 11. Performance of different coolant pumps from Pierburg [152].

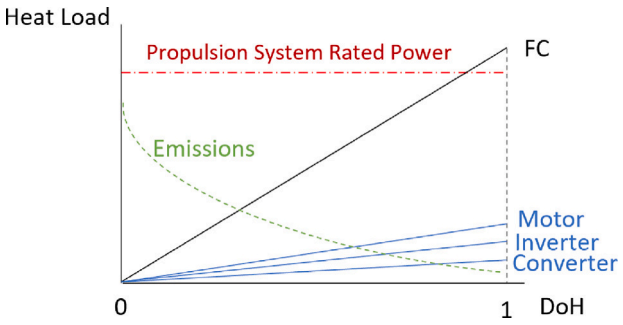

Fig. 12. A qualitative representation of FC heat load vs Degree of Hybridization.

They are already used in stationary, space and automotive applications and are currently being considered for aerospace. Fuel cells are electrochemical cells that convert fuel energy into electric energy through a catalytic process. They consist of the anode (fuel side), cathode (oxidant side) and a membrane which serves both as a separator between the reactants and as an electrolyte that facilitates the proton exchange [153]. These three components comprise the membrane-electrode assembly. There is a catalyst layer on each side of the membrane and a porous gas diffusion layer which allows the diffusion of the reactants to the catalyst layer. The distribution of the reactants to the gas diffusion layer is facilitated by a bipolar plate. Cooling channels are integrated into the bipolar plates to remove the produced heat [154].

There are different types of FCs which are classified based on the type of electrolyte they use. The types of fuel cells and their main characteristics are summarized in Table 5. All FC types involve a hydrogen oxidation reaction at the anode [155] but some types can be fuel flexible by using either direct internal reforming, in the case of Solid Oxide Fuel Cells (SOFCs), [156,157] or by external reforming which requires power consumption. However, direct hydrogen use has attracted a lot of interest because it eliminates carbon emissions and avoids the parasitic loss of the reformers. Fuel cells are available in stacks each of them consisting of a number of cells and the stacks can then be arranged in different configurations to provide the required power to the aircraft and the selected voltage for which the electric system is designed [158].

Kazula et al. [159] qualitatively reviewed the different types of fuel cells and proposed a scoring method for evaluating their suitability for aerospace applications. The scoring criteria included efficiency and performance, weight, ease of integration, safety, reliability and life cycle costs, and development and manufacturing costs. The FC types that scored the highest score were SOFC, High-Temperature Polymer Electrolyte Membrane Fuel Cell (HT-PEMFC) and Low-Temperature Polymer Electrolyte Membrane Fuel Cells (LT-PEMFC), in this order of suitability. Waddington et al. [160] also compared PEMFC against SOFC for integration in Boeing 737–800 in a quantitative approach. They observed that HT-PEMFC produced less power and thrust than SOFC due to the parasitic losses for air pressurization. Despite the potential superior performance that SOFC can exhibit over PEMFC due to their higher operating temperatures, their lower level of maturity for aircraft application and lower power density were considered prohibitive for aircraft at that moment. Another reason the authors did not further consider SOFC as they are not zero Nitrogen Oxide (NOx) which was a target for that study. So far, more aircraft concepts have focused on implementing PEMFC either as a primary energy source or auxiliary energy source [161–169]. SOFCs have been mainly considered as an auxiliary power unit in aircraft [170–172], but they also offer promising opportunities for integration with the gas turbine cycle to improve the overall efficiency [173–175]. The HT-PEMFC technology is still at low TRL, while LT-PEMFC products are commercially available for other transport applications but are under testing for aircraft. SOFCs are commercially available for stationary applications.

8.1. Thermal challenges

The heat generation at the fuel cell is attributed to the exothermic electrochemical reactions between the anode and the cathode, the ohmic losses and the condensation of the water vapor [179]. A typical fuel cell stack efficiency is around 50%–60% which means that up to half of the produced energy is dissipated as heat which poses a great thermal management challenge for fuel cells. The inefficiency of the FC has been broken down to primarily heat load and a small fraction of unused fuel [177,180]. However, a very small part of the heat is removed as enthalpy of the exiting water exhaust or excess fuel and it does not require removal by the thermal management system [181]. In contrast, in gas turbine propulsion systems, most of the heat waste is readily rejected in the atmosphere with the exhaust jet. Some individual hot-section components such as the combustor liner and high-pressure turbine vanes and blades usually require some heat to be removed so that their material limits are not exceeded but this cooling requirement is managed “internally” by extracting bleed air from the cold section before the combustion and diverting it to cool the required components [182]. Fuel cells require an external thermal management system for heat removal which comes with a significant mass and drag penalty. The heat generation of fuel cells can be expressed as a function of the output power of the electric power system and the efficiencies of the components of the powertrain (assuming that the fuel utilization factor at the FC is 1 and there is no unused fuel):

$$P_{heat} = \frac{PowerOutput}{\eta_{mot} \cdot \eta_{inv} \cdot \eta_{conv} \cdot \eta_{FC,inclBoP}} (1 - \eta_{FC,stack}) \quad (10)$$

Considering the power losses at the rest of the electrical system and that the fuel cell efficiency is at its lowest during take-off power [164], the fuel cell heat generation can even exceed the rated power of the propulsion system for an FC aircraft (see Fig. 12). For a fully electric aircraft or hybrid electric aircraft with a constant degree of hybridization, the maximum FC heat loads are experienced during take-off. Adding further to this challenge, during take-off the temperature difference with the ambient air is the lowest of the flight and the air velocity is still relatively low compared to cruise. A low velocity reduces the convection and makes heat dissipation more challenging and requires large heat transfer areas. For LT-PEMFCs that operate around 80 °C the temperature difference during a hot day take-off can be as low as 40 degrees resulting in low heat transfer rates, depicted in Fig. 13. Cruise conditions offer a more beneficial combination of moderate heat load, high air velocity, and low ambient temperature. Stoia et al. [167] calculated that designing an FC cooling system for cruise conditions results in a lighter system than take-off conditions.

Efficient cooling is critical for FC as an increase in the temperature of the fuel cell beyond its limits affects both the membrane’s durability and its performance. The fuel cell membrane needs to remain

Table 5
Fuel cell types [155,176–178].

	Polymer electrolyte membrane FC	Phosphoric acid FC	Alkanine FC	Molten carbonate FC	Solid oxide FC
Electrolyte	Polymer membrane	Liquid H3PO4	Liquid KOH	Molten Carbonate	Ceramic
Catalyst	Platinum	Platinum	Platinum	Nickel	Perovskites (Ceramic)
Operating Temperature	<120 °C	<200 °C	<100 °C	600–700 °C	500–1000 °C
Fuel	H2, methanol	H2	H2	H2, CH4	H2, CH4, CO

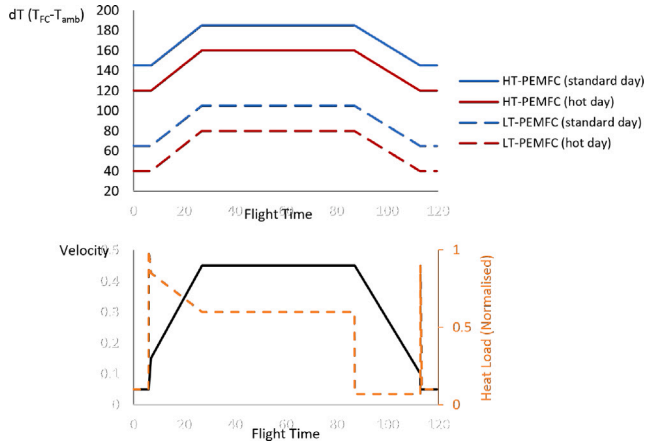

Fig. 13. Temperature difference between the FC and the ambient environment, heat load and velocity during a typical flight (based on data from [164]).

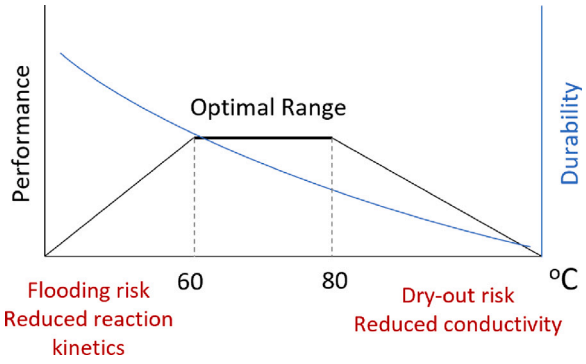

Fig. 14. LT-PEMFC optimal temperature range.

properly hydrated to maintain a good ionic conductivity so if the membrane dries out the proton transport reduces, and the efficiency deteriorates [153]. Both membrane dry-out and overflooding must be avoided to ensure proper operation of the fuel cell, and it has been highlighted [154] that maintaining the operating temperature within a narrow optimal range is an important factor in membrane water management. A very low temperature affects the water saturation pressure posing a risk of flooding while a very high temperature above 85–90 °C poses a risk of dehydration reducing the conductivity and mechanical stability of the electrolyte membrane [183].

8.2. Effect of the operating temperature

Fuel cell operation is based both on mass transport mechanisms and electrochemical reactions facilitated by a catalyst. From a mass transport perspective, a high temperature accelerates mass transport through the gas diffusion layer which has a positive effect on the performance [183,184]. From an electrochemical point of view, an increase in the temperature reduces the Gibbs energy and the reversible potential which negatively affects the efficiency but tends to enhance the reaction kinetics and ionic conduction [184]. From a cooling effectiveness perspective, it becomes more challenging to remove lower-grade heat from a component as the difference between the fuel cell and the ambient temperature reduces which reduces the heat transfer rate. From a durability perspective, a higher temperature enhances the degradation mechanisms and reduces the life of the membrane and catalyst [183,185]. From a water management perspective, today's fuel cells operate optimally when the membrane has a suitable water content [186] in order to maintain a good ionic conductivity, while a temperature increase beyond 85–90 °C increases the water evaporation and poses a risk for membrane dehydration. The operating temperature has a complex combination of effects on the participating mechanisms. It is important to maintain the fuel cell operating temperature within the optimal range to ensure both performance and durability targets are met, indicated in Fig. 14.

On the other side, the gas turbine thermal efficiency and performance tend to improve with an increase in the operating temperature as long as it is combined with the optimum pressure ratio and bypass ratio (in the case of turbofans) [187,188]. Upper limitations are still present due to the material limits and the losses coming from the increased cooling requirements, but from a thermodynamic perspective, higher operating temperatures are preferred in gas turbines. The turbine entry temperatures of modern gas turbine engines have been continuously evolving and can be as high as 1600 °C in modern engines [189].

8.3. Efforts to tackle the thermal management challenges in fuel cells

An overall issue in electric and hybrid electric aircraft is the absence of sufficient heat sinks to reject the heat loads without excessively increasing the mass and drag penalty at the aircraft level. High heat loads at low temperatures require larger heat transfer areas, and increased coolant flows, hence, increasing the mass of the heat exchangers and overall system. The thermal challenges in FC aircraft necessitates both technology advancements and integrated system solutions maximizing the benefit from the available heat sinks while minimizing drag and mass. At the component level, there are efforts to mitigate the thermal management challenges of fuel cells through technology improvements in three main areas:

- increasing the operating temperature of the fuel cell through improved materials
- optimizing the cooling technique and the internal cooling passages
- improving the fuel cell efficiency so that less fuel energy is wasted as heat load and more energy is converted to useful electric energy

Especially high-temperature PEMFC technology aims to improve both efficiency and thermal management through increased temperatures (see Fig. 13) and good membrane ionic conductivity without water content as the water exists in the gas phase. The need for maturing high-temperature PEMFC technology has been highlighted in roadmaps towards net zero [190,191]. SOFC technology is also promising for aircraft application [159,160,173] but currently it is behind PEMFC in terms of power density, volumetric density, start-up times and transient times. If SOFC technology catches up on these areas, their implementation will ease some of the thermal management challenges as they have higher efficiencies and higher operating temperatures, hundreds of degrees higher than PEMFC, which means that the heat would be dissipated with smaller heat transfer surfaces.

8.3.1. High-temperature membranes

To enable high-temperature fuel cells to go above the operating temperatures of today's fuel cells new materials for membranes are being developed. A higher operating temperature is paramount for enhanced reaction kinetics and effective heat dissipation but current LT-PEMFC polymer membranes rely on water hydration for good ionic conductivity, which limits their performance above 85 °C when water evaporation increases. Research efforts are focused on developing and optimizing high-temperature dry membranes that have good durability and conductivity at high temperatures without relying on hydration. Perflurosulphonic acid (PFSA)-based polymer membranes are today's standard for LT-PEMFC which come under different brand names such as Nafion, AQUIVION, Aciplex and Flemion [183]. For HT-PEMFC, phosphoric-acid dopped polybenzimidazole (PA-PBI) membranes are mainly considered. The acid-doping facilitates the proton transport [192] so they have good ionic conductivity at high temperatures without relying on hydration so they are potential enabling materials for fuel cell operating temperatures above 120 °C. However, current issues related to premature acid loss and catalyst poisoning by absorbing phosphoric acid limit their performance and durability [193]. According to [194,195], there is a gap in appropriate membrane materials with good conductivity in the temperature range of 80–120 °C. Conventional PFSA membranes have good conductivity up to 85 °C above which they suffer dehydration and PA-PBI dry membranes have good conductivity at high temperatures above 120 °C. For this reason, there are also research efforts focusing on manufacturing improvements to polymer membranes such as polymer–ceramic composite membranes which can fill the gap between 80–130 °C by adding a ceramic phase (filler) to the polymer that can improve water retention [192] or proving that polymer membranes operating at higher pressures can have good hydration and performance above 90 °C [185].

8.3.2. Cooling techniques

Small-scale stacks with power below 10 kW can be cooled sufficiently with passive cooling and air cooling. For large stacks of power > 10 kW, which are required for aerospace applications, liquid cooling using water or water–glycol mixture is required and as the power of the stack further increases phase change cooling becomes more beneficial [154,177,181,196]. Phase change cooling takes advantage of the large amount of latent heat absorbed or released during the phase transition at the evaporator or condenser respectively. The type of cooling affects the required amount of coolant mass flow and the size of the coolant passages within the stack to maintain the optimal temperature range, therefore, it is an important factor in the fuel cell power density. Evaporative cooling has the potential to increase the power density of the fuel cells [197,198] but there are challenges related to the operational stability and control of the system [198]. In [196], it was calculated that the implementation of water evaporative cooling using an aluminum condenser reduced the radiator frontal area by 27% subject to sufficiently high liquid water separation efficiency. Some studies considered a phase change cooling system integrated directly with the fuel cell stacks [199,200] while other concepts propose a liquid cooling loop passing through the cooling channels of the fuel cell and a heat exchanger–evaporator to remove the heat of the liquid coolant with a phase change system [201]. Choi et al. [200] proposed a phase-change cooling system with boiling for LT-PEMFC using as working fluid HFE-7100 with a boiling point of 61 °C.

Nanofluids [202–204] and PCMs [199,205] have also been suggested as candidate cooling solutions in generic FC studies but have not been given much attention for FC in aircraft applications. Nanofluids have excellent thermal conductivity and result in increased convective heat transfer when dispersed in a base cooling fluid so they have the potential to decrease the heat exchanger size [203,205] but they cause a higher power consumption due to the increase in density [206], have challenges with stability during their preparation [202] and their maturity is still low. Phase-change materials take advantage of the great heat capacity and absorbed latent heat during the phase-change without the need for auxiliary power consumption [32]. Although PCMs have medium maturity for cooling batteries [13,32] there is less research on their application to FC, especially for aircraft applications. Their transient performance during a flight, whether they provide sufficient temperature control for FC propulsion systems, the volume changes [207] and other challenges that may arise in FC aircraft applications have not been researched sufficiently. Overall, although nanofluids and PCMs offer advantages, they have very low maturity for FC propulsion.

8.3.3. Cooling passages

Further benefits can be accrued by optimizing the coolant distribution to improve the heat transfer properties of the flow and increase the heat transfer area and the uniformity of the temperature distribution [177,208]. Alizadeh et al. [209] compared nine coolant channel designs and evaluated them based on temperature uniformity, mass flow rate, maximum temperature difference of the coolant and minimizing the pressure losses. Afshari et al. [210] proposed zigzag-shared cooling channels and computationally calculated clear benefits over straight channels in terms of maximum temperature, temperature difference, and temperature uniformity. Saeedan et al. [211] investigated numerically the coolant air distribution through a porous metal foam medium and varied the porosity. They identified that a reduced porosity increased the pressure drop which is undesirable but increased the thermal conductivity due to the increase of the solid material and the uniformity of the temperature distribution. Shen et al. [212] investigated four different ways of water distribution in the coolant passages; unidirectional flow cooling, reverse flow cooling of the interlayer channels, reverse flow cooling of the adjacent channels, and bidirectional circulation cooling. The highest temperature uniformity within the stack, efficiency, and power density was observed for the reverse flow direction of adjacent channels and the bidirectional circulation cooling.

8.3.4. Efficiency improvement

Improving the efficiency of the fuel cell and increasing the useful output power is another medium to reduce heat losses. The efficiency of the fuel cell stack can be improved through higher temperatures to accelerate mass transport through the gas diffusion layer and reaction kinetics. Higher temperatures will be enabled by membrane material improvement and transition to HT-PEMFC. A significant part of the heat load comes from the ohmic losses due to the resistance of the membrane and catalyst layer. The resistance of the electrolyte-membrane is inversely proportional to the conductivity and is a function of the membrane thickness. Some efforts have been focusing on optimizing the membrane thickness to reduce the resistance and improve the conductivity. Membrane thickness is a trade-off between increased conductivity and reduced mechanical strength. Improved manufacturing methods with reinforcement layers have allowed membranes to become thinner over time [213]. Platinum-based catalysts are still the dominant material considered for LT and HT PEMFC [193,214]. Some researchers have focused on improving the catalyst layer support conductivity and durability [193] or investigating the optimum manufacturing methods of the membrane electrode assembly [215].

8.4. Proposed cooling systems for FC aircraft and emerging technologies

Stoia et al. [167] performed the conceptual design of a pumped liquid cooling system for a 20MW HT-PEMFC aircraft (CHEETA project) that rejects the FC heat to the environment through a ram air heat exchanger and estimated that when sized for take-off it will have a mass of 708 kg. For a LT-PEMFC they estimate that the thermal management system is approximately four times heavier. They conclude that a two-phase pumped system should be the next step as it is feasible to evaporate the working liquid under the elevated operating temperatures of the HT-PEMFC and heat load of 16 MW at an evaporator

that is in contact with the FC end plate or cooling passages and the ram heat exchanger can condense the vapor back to the subcooled state. Affonso et al. [201] proposed thermal management concepts for future electric and hybrid electric aircraft and proposed an ethylene–water mixture liquid loop to cool down the fuel cells. The cryogenic hydrogen needs to be heated and vaporized before being used in the fuel cell, consequently, there is an opportunity to reject part of the heat from the ethylene–water loops that cool down the electric components, fuel cell, and batteries to the cryogenic hydrogen before it is utilized in the fuel cell. Renau et al. [216] proposed a cooling air system for an HT-PEMFC powering in an Unmanned Aerial Vehicle (UAV) operating at high altitude mission (10 km) using a glass-fiber fuselage around the FC stack to drive the airflow, a cone and valves to control the amount of cooling air and regulate the stack temperature. They estimated that the penalty in power consumption can be less than 2.75%. ZeroAvia [217] performed a test flight with a 19-seat aircraft using LT-PEMFC. They project that the turbo-air cooled HT-PEMFC currently under development which will have higher pressure and operating temperature will allow adopting an "active" air cooling with reduced mass and drag penalty. Further details about the cooling system are not publicly available. Universal Hydrogen is developing FC system retrofit kits for regional aircraft and performed a 15-min hybrid flight testing a 800 kW FC [218]. The only available information on the cooling system is that it features large air ducts [218] but further details of the thermal management system are not published.

9. Cables

In the traditional aircraft design, the gas turbine is used primarily to provide thrust and secondarily as a source of power for additional loads in an aircraft. These loads come from electrical, pneumatic, mechanical and hydraulic systems which are responsible for avionics, cabin pressurization and oil pumps, and flight controls (e.g. elevators, rudders) respectively. This load distribution into different subsystems has evolved over time. Different voltage standards for traditional aircraft designs exist. They include:

- 28 VDC for small electrical loads on large aircraft and the entire electrical system on small aircraft,
- 270 VDC for military applications and some subsystems on larger aircraft and
- 115 V VAC at 400 Hz for large aircraft [219]

The transition to MEA, later to HEP leads to increased performance requirements on the electrical system that cannot be met by traditional standards. Even emerging standards that are adopted in many MEA and HEP concepts and include 540 VDC (±270 V), 230 VAC at 400 Hz, and 230 VAC at 320–800 Hz cannot cope with the additional power demand and the associated increase in current and/or voltage. The expected voltage level for hybrid-electric regional flight missions is < 1000 V, and for hybrid-electric short- and medium-range missions > 3000 V [71].

9.1. Current and voltage limits

The maximum current in metallic conductors is expressed by the ampacity. It takes into account heat generation due to ohmic losses in the conductor which can be expressed by Eq. (11). The ampacity at ambient conditions can be influenced by the design of the conductor cross-section as well as the choice of material [220]. High-ampacity power transmissions are busways/ bus bars or power cables/ cable busses typically made out of copper or aluminum. An increase above the ampacity threshold requires cooling so that thermal runaway can be prevented.

$$P_{Loss,Joule} = I^2 \cdot R \tag{11}$$

The current–voltage level of 115 VAC at 400 Hz or 270 VDC is determined by Paschen's law [221]. The breakdown voltage is a function of the gas pressure and thus flight altitude as well as the distance between the electrodes and thus insulation. Increasing the voltage above this will result in high voltage losses and safety hazards such as arcing, partial discharge, and space discharging if not properly designed [71,221–224].

9.2. Electrical and thermal insulation

To protect the conductors against external harm insulation is used. Polyimide (PI), ethylene-tetrafluoroethylene copolymer (ETFE), polytetraflourethylene (PTFE) or polyurethane (PU) are typically chosen in aerospace applications [220]. The choice of insulation materials is based on various characteristics such as temperature resistance, electrical performance, flammability requirement, mechanical and chemical strength, weight saving, and the routing [225]. To determine the thickness and thus the weight of an insulation, the minimum breakdown voltage is determined for a given insulation material. Taking into account a safety factor of five (rule of thumb), the electrically required insulation thickness can be determined [220]. Mechanical boundary conditions can lead to greater insulation thicknesses too.

9.3. Cryogenic applications

Another possibility for the realization of high-performance applications is the introduction of cryotechnology or high-temperature superconductors [78,82,83,226,227]. By cooling the conductors with liquid or gaseous helium, liquid hydrogen, or liquid nitrogen, the critical temperature of the conductor can be undercut so that no electrical resistance exists in the conductor [79]. Thus, ohmic losses do not occur even at very high currents, which means that traditional voltage standards can be maintained with the highest efficiencies [220]. Selecting a proper type of coolant (e.g. H2-based) is based on aircraft architecture and thermal conductor characteristics. Potential conductor materials are NbTi, MgB2, Bi-223, YBCO or ultra-pure aluminum [79,220]. Electromagnetic concerns at cryogenic temperatures of the conductor and its' insulation must be considered. Low temperatures can lead to deviation in the aging process and to tolerance against electric, magnetic, thermal, and mechanical stresses of cryogenic insulation materials like microsphere insulation systems (MLS) and multilayer insulations (MLI). These superinsulations have thermal conductivity between 0.1 W/(m.K) and their performance is related to vacuum levels of the cooling system [228]. To withstand transient increases of temperature in the conductors and counteract vacuum degradation over time, monitoring is required [229]. Otherwise, loss of superconductivity characteristics leads to hazardous events and therefore low reliability of the overall cooling system [230]. By implementing cryo or superconducting technology into the power distribution system, a significant weight reduction can be expected [220]. But, technology readiness is low and therefore an imminent implementation in aeronautical applications is not expected [231].

10. Coolants and plumbing

A fluid flow is required for any TMS to transport the heat load from the source to the location of dissipation. The type of fluid and the mode of heat transfer depends on various factors such as the location of the heat source, the magnitude of heat loads, and allowable pressure drops. The mode of cooling ranges from single-phase liquid or air cooling to two-phase cooling.

Table 6
Types of coolants.

Coolant	Application	Reference
Water, Brayco Micronic, Dynalene HF-LO, Dielectric coolant FC-84, Novec-7200, Ethylene glycol–water, Propylene glycol–water, Engine oil, Mobil jet oil, Paratherm LR, RF 245 FA, Silicone KF96, Skydrol 500-4, Fluorinert oils, Baysilone oils, Jet fuel, Refrigerants, Liquid Hydrogen, Liquid Nitrogen, Liquid Helium, Liquid Neon	Electrical machines	[43,78–80,233,236–238]
Water, Ethylene glycol–water, Propylene glycol–water, Mineral oil, Silicone oil, Novec 7000, Metallic nanofluids, Liquid metals, Liquid Hydrogen	Battery	[131,132,228]
Water, Ethylene glycol–water, Mineral oil, Novec 649, Novec 7000, FC - 72, FC - 43, FC - 3283, Liquid metals, Liquid Nitrogen, Liquid Hydrogen	Power Electronics	[142–145,234,235,239]
Water, Ethylene glycol–water, Kerosene hydrocarbons, Nanofluids, Liquid Hydrogen	Fuel Cells	[180,201]

10.1. Types of coolants

Air is commonly the preferred heat transport medium due to its abundant availability. It can be used to cool the components directly [34–36,43,232] or carry away the heat from the coolant in the heat exchanger [34–41,43–45]. The airflow is driven either by a fan or inlet ram effect. The airflow rate or the flow control generally depends on the duct design, aircraft speed, fan speed, and arrangement of the components in the duct.

Air is not always an effective coolant, particularly for the larger heat loads observed in aircraft applications. Various liquid coolants can be used to achieve the cooling of electrical components. A coolant that is used for the electrical components should have the following properties (depending on the mode of contact with the component) along with excellent thermal properties [233]: non-toxic, non-flammable, anti-corrosive, chemically inert, and stable, low dielectric constant and high dielectric strength. Advance cooling methods such as cryogenic cooling are also being explored to achieve higher power densities in electric aircrafts [78–80,131,132,142–145,201,234,235]. Details of cryogenic cooling are already presented in the cooling technologies corresponding to each component in the above sections. Different types of coolants shown in the literature according to the component they are used for are summarized in Table 6. In general, a good choice of the coolant and heat transfer surfaces promotes better TMS performance.

10.2. Plumbing system — pipes

A coolant flow from two components is the basis for heat transfer/transport in a TMS. Typically, a plumbing system has to be set up to support the coolant flow. Pumps, valves, tanks, and pipes together constitute a plumbing system. Pumps and hydrogen tanks are explained in detail in their corresponding sections. Conventional pipes of smaller diameter can be used to carry the coolant. Aluminum and copper are commonly used as pipe material [240–242]. The length of the pipe depends on the aircraft design and the arrangement of the components to be cooled. Longer coolant pipes can result in higher pressure drops and might result in higher pump power.

11. Hydrogen storages and tanks

Hydrogen storage onboard aircraft has garnered significant attention due to its remarkable impact on aircraft configuration, weight, and overall performance. Although hydrogen possesses a high heating value of 120 MJ/kg, approximately 2.8 times that of kerosene, its extremely low density presents challenges, making cryogenic storage the only viable option. The automobile sector has proposed storage at 700 bars, resulting in a density of 40.2 kg/m3 and a volumetric energy density of 4.8 GJ/m^3, in contrast to kerosene's 35.5 GJ/m^3.

11.1. Challenges

Even in its liquid state at 20 K and 1 bar, with a density of 70.8 kg/m^3, hydrogen exhibits a volumetric energy density of 8.5 GJ/m^3, which means it requires over four times the volume to store the same amount of energy as kerosene. Extensive research [243,244] has been conducted to explore various storage methods, and liquid storage has emerged as the most suitable and widely accepted option for civil aviation.

Due to its large volume requirements, hydrogen cannot be efficiently installed in the wings, and, therefore, in most studies, it is placed in the fuselage. Even storing part of the hydrogen in the wings poses challenges, as the surface-to-volume ratio of a wing-conforming shape tank is larger than that of a cylindrical tank, leading to higher heat losses. As a result, practical considerations strongly favor the adoption of large cylindrical liquid storage for hydrogen in aircraft.

Any heat leakage into the tank results in the vaporization of some liquid, leading to an increase in tank pressure. This rise in pressure is more pronounced in the vapor phase, causing a vertical temperature gradient to form. Numerous studies, backed by experimental results, have focused on understanding pressurization and temperature stratification in the tank [245–249].

Efforts to insulate the tank and maintain hydrogen in its liquid state have been extensively investigated, particularly for long-term storage applications in spacecraft [250–253]. In scenarios where the pressure in the tank reaches its design limit, some vapor must be vented overboard to manage the pressure levels effectively. For long-term storage designs in space applications, insulation using a vacuum jacket, typically layered with reflective material to minimize radiation (known as multi-layer insulation), is the preferred approach. However, it is important to note that space conditions differ significantly from those in the atmosphere, particularly in civil aviation. Firstly, maintaining a vacuum in space is relatively straightforward, and any loss of vacuum in the insulation can severely degrade its thermal conductivity, often by two orders of magnitude [254]. Secondly, in space applications, the focus is on minimizing the overall weight of the tank and vented vapor, rather than just the weight of the tank itself. Consequently, long-term space missions often favor heavier insulation to prevent hydrogen venting. This approach also proves advantageous for long-endurance applications like UAVs operating in the atmosphere, where vacuum insulation has demonstrated superior performance [255]. Lastly, power requirements in space are typically lower compared to aircraft. In civil aviation applications, hydrogen removal from the tank gradually reduces the pressure and effectively balances out heat ingress during the cruise, thus reducing the insulation requirements.

In summary, while vacuum insulation remains a popular choice for space applications, its suitability and performance differ in the

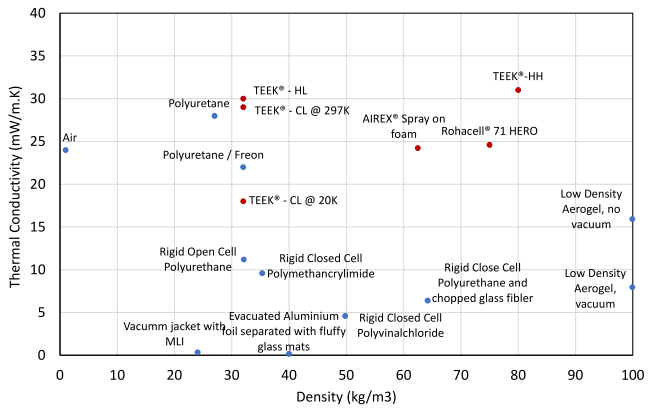

Fig. 15. Insulation properties of selected materials. Red dots indicate commercial materials obtained from [251,255,262,268]. Blue dots generic materials from [243, 255,259].

unique conditions of the atmosphere during civil aviation missions. The distinct factors such as vacuum maintenance, weight considerations, and power requirements influence the insulation approach chosen for each application.

Space applications benefit from incorporating more complex venting systems [256] or refrigeration power to achieve zero-boil-off conditions [257,258]. Foam insulation is the preferred choice for short-term storage of the main cryogenic tanks in space launch vehicles, such as the space shuttle [250]. Extensive research has been conducted on foam insulation [243,255,259–262], and its properties are illustrated in Fig. 15. Foam insulation has been favored in numerous previous studies on Hydrogen Aircraft [259,263,264]. Additionally, aerogels have been analyzed as they can offer similar performance to some foams [255,260,265].

The material used for the tank's inner wall must prevent hydrogen permeation and avoid hydrogen embrittlement at cryogenic temperatures. A comprehensive study on the susceptibility of metallic materials to hydrogen embrittlement was carried out for the space shuttle (Lee, 2016). For space applications, aluminum is typically used due to its maximum specific strength and its resistance to hydrogen embrittlement. While composite tanks have been studied, they require a liner to prevent hydrogen permeation and must be designed to prevent microcracking during thermal cycling [255,266,267].

Vacuum-insulated tanks offer the flexibility of an outer wall made of either metallic or composite material. However, research by Sullivan et al. [255] indicates that there is little advantage of using composite material over metallic in terms of buckling/crippling failure mode.

When it comes to foam or aerogel-insulated tanks, incorporating an outer composite wall can provide an added layer of protection, preventing contamination and reducing the risk of detachment of the foam. This approach has been studied, as demonstrated by Winnefeld et al. [269], who investigated the performance of ellipsoidal tanks with various aspect ratios. Their findings revealed a deterioration of thermal performance as the surface-to-volume ratio of the tanks increased. Moreover, a comprehensive parametric study conducted by Huete and Pilidis [270] explored the impact of tank size, technology, architecture, and insulation choices. This study sheds light on the crucial factors influencing the overall performance of the tanks under different configurations and scenarios.

Fig. 16 shows the gravimetric efficiency of the tank as a function of the radius of the tank. Gravimetric efficiency has been calculated as the mass of stored hydrogen at the maximum allowable pressure or venting pressure divided by the mass of the tank plus the stored hydrogen. An additional 300 kg of accessories to make an allowance for buffers, instrumentation, and fuel feed manifolds has been added. Other design parameters are as follows: maximum allowable pressure:

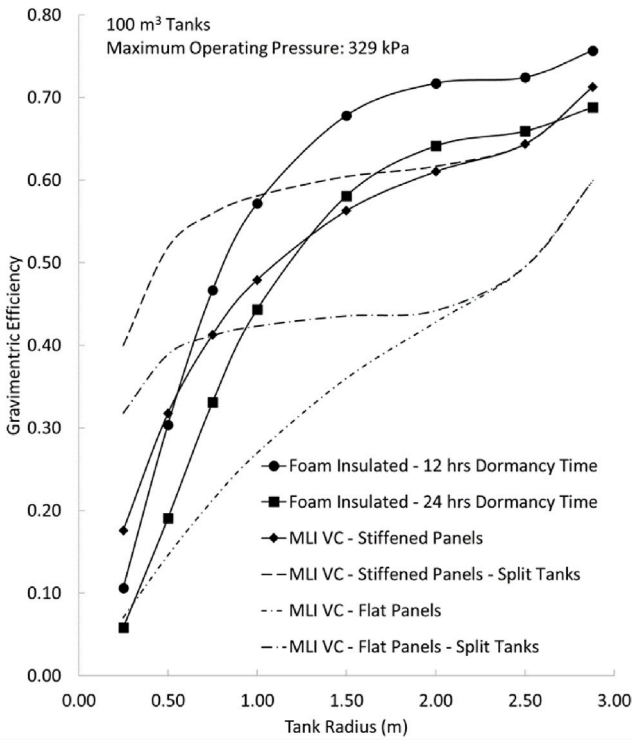

Fig. 16. Effect of tank radius on gravimetric efficiency.

329 kPa (equivalent to 25 K vapor liquid equilibrium), pressure at fill: 163.5 kPa (22K), safety factor mechanical design: 2.2, the minimum thickness of Aluminum wall: 0.8 mm.

It should be noted the large difference in gravimetric efficiency obtained at different tank radius. This effect was also recognized by (Verstraete et al. [261]) for foam-insulated tanks. This fact underpins the large variation in gravimetric efficiencies found in the literature and explains the different optimum designs depending on the range of the application and maximum fuselage size. The existence of an optimum radius for foam-insulated tanks is also visible in [261] and in [269], although it is not discussed there. The optimum radius for a 100 m^3 foam-insulated cylindrical tank is between 2 and 2.5 m, higher for longer dormancy times with thicker insulation. As the tank approaches a sphere (radius 2.88 m), there is a discontinuity since the mechanical performance of the sphere is superior and gravimetric efficiency reaches an absolute maximum. Vacuum-insulated tanks have a dormancy time in the order of hundreds of hours and therefore, only one line has been drawn for each type. Regarding weight considerations, these tanks perform unfavorably for dormancy time requirements below 24 h, barring instances with extremely low radius. However, foam or aerogel-insulated tanks are relatively less advanced in applications demanding prolonged endurance. Addressing this gap necessitates a substantial R&D investment focusing on mitigating challenges such as foam detachment and assessing performance when exposed to various gas contaminations.

11.2. Tank placement and cabin layout

The research presented by Huete and Pilidis [270] provides valuable insights into the rationale behind placing tanks inscribed in the fuselage — primarily to enhance gravimetric efficiency and reduce aircraft weight. However, this configuration comes at the cost of compromising passenger capacity, necessitating a wider and longer passenger cabin to accommodate travelers.

The available studies lead us to the conclusion that a hydrogen-powered aircraft with a passenger capacity of around 200 and a range

between 2000 to 3000 nm is no longer designed as a single-aisle aircraft. Only Cryoplane retained the 6-abreast configuration but shifted the tanks to the top, departing from the conventional cylindrical tube and wing arrangement. In all other studies, tanks are placed at the rear, with some also positioned at the front. For medium-range aircraft, a double aisle design becomes more practical, but this entails carrying the additional weight of an extra aisle and an increased fuselage diameter. This prompts the question of determining the maximum passenger capacity and range achievable for a single-aisle aircraft, as well as the maximum fuel storage capacity in the rear cone without compromising longitudinal stability.

Regarding long-range aircraft, studies have explored double-deck designs with tanks located both at the front and rear of the passenger cabin, as well as unconventional configurations featuring longitudinal tanks on top of the fuselage. While the former option is feasible, it does come with several additional challenges. On the other hand, the latter option, though intriguing, poses additional penalties for hydrogen-powered aircraft. In the following sections, we will analyze the maximum passenger capacity and range that a single deck, conventional tube and wing aircraft can offer.

To accommodate a forward tank, separate doors and facilities for the cockpit crew and cabin crew/passengers are necessary. Emergency evacuation provisions for cockpit crewmembers should be made, possibly through the implementation of a new top hatch, as specified by the European Union Aviation Safety Agency [271]. Without a walkway between the cockpit and cabin, certain considerations must be taken into account, as acknowledged during early discussions on pilot-cabin communication [272] and analyzed in SKYbrary Aviation Safety [273,274]. These considerations include the need for separate doors for the cockpit and cabin, the placement of toilets near the cockpit area, possible enhancement of cockpit security but with the potential need for additional crew at the cockpit, the incorporation of a separate emergency exit for the cockpit crew, and the possibility of emergency passages for visual inspections of engines and control surfaces by the cockpit crew.

In addition to these considerations, a separate emergency passage could be designed either on one side of the forward hydrogen tank or through a specially designed passage through the cargo deck at a lower level, in case regulations require independent access for emergency situations.

Top tanks or longitudinal tanks on top of the fuselage must be designed as low-diameter tanks, which can lead to increased tank weight in comparison to the weight of stored hydrogen. Additionally, the enlarged cross-section of the fuselage contributes more weight and drag compared to fuselage longitudinal extensions. While major aerodynamic challenges are generally not a concern, as demonstrated by aircraft like the Airbus Beluga and others with similar configurations, this setup does impact the overall weight and range of the aircraft. As a consequence of this design, energy efficiency is likely to diminish, and the performance might be inferior to that of a conventional cylindrical tube and wing solution. The added weight and drag, coupled with the constraints of accommodating low-diameter tanks on top, pose significant challenges that can limit the aircraft's range and efficiency.

11.3. Hydrogen tank architectures and aircraft weight

Storage-related studies on medium-range aircraft can be categorized into two groups: those utilizing vacuum-insulated tanks (Cryoplane and Clean Sky) and those employing foam-insulated tanks (Brewer, Verstraete, FlyZero, ENABLEH2) [275,276]. The former category requires heavy tanks, around 30 tonnes, to carry approximately 20 tonnes of liquid hydrogen for an equivalent mission to existing narrow-body aircraft. Due to the substantial fuel quantity, it becomes impractical to install rear tanks, as the varying center of gravity between a full aircraft with empty tanks and an empty aircraft with full tanks cannot be effectively managed with conventional control surfaces. Thus, these studies use either tanks placed at the rear and front or top tanks. On the other hand, the latter category utilizes significantly less hydrogen (around 6.6 tonnes) stored in tanks that weigh just a few tonnes. As a result, rear tanks can be used, making the aircraft much lighter and necessitating smaller wings and engines. The Operating Empty Weight (OEW) for aircraft in this category ranges from 48 tonnes (FlyZero) to 58 tonnes (Verstraete), with the differences arising from the hypotheses employed in each study.

The variations in long-range aircraft studies are even more significant due to the impact of larger fuel quantities and passenger capacity. In Cryoplane and Clean Sky studies, the amount of liquid hydrogen is approximately double that of other studies for a similar mission, resulting in larger and heavier aircraft. However, the varying OEW estimations among different studies cannot be solely attributed to tank weight but also to the differing hypotheses and constraints used. Brewer's study made optimistic estimations by employing technologies forecasted to be available in 1985, allowing the operational capability of the aircraft by 1990–1995. He integrated several advanced technologies still under development, forecasting performance based on initial experimental results or extrapolating trends observed in previous component generations. These assumptions led to weight estimations larger than today's very long-range aircraft while still being 30 to 50 tons lighter despite adding 10 tons of cryogenic tanks. Verstraete's estimations used NASA FLOPS correlations and state-of-the-art technology without considering technology improvements. However, unusual values of wing loading at landing were considered, which could result in unusual approach speeds and landing lengths or necessitate advanced high lift devices and increased noise. The work led by FlyZero incorporated technology factors to reduce the estimated weight of various aircraft and engine components by approximately 5%–7%. They also considered aerodynamic efficiency and engine efficiency in their estimations. The impact of weight estimation on the rest of the analysis is significant, affecting wing area, installed power, range, and energy efficiency. These factors have an exponential effect on the overall aircraft performance.

12. Conclusion

The current study undertakes a thorough examination of the latest advancements and obstacles within the realm of thermal management systems for hybrid-electric propulsion aircraft technology. The TMS is dissected into two categories: the components necessitating TMS and those facilitating it, namely electrical machines, heat exchangers, batteries, power electronics, pumps and fans, fuel cells, power distribution, coolants, and storage. After delineating these components, and encompassing their classifications and types in HEP contexts, the paper identified the thermal-related challenges that impede the practical integration of an efficient TMS in a HEP setup. Furthermore, we summarized and highlighted the endeavors aimed at addressing these challenges.

According to the literature, almost all the elements shaping a TMS need to be modified and the related thermal challenges are to be addressed before a safe and reliable HEP flight can happen. Among the emerging technologies reviewed for each of the elements, cryogenic cooling has repeatedly been addressed, that is for electric machines, batteries, and power electronics. However, although hydrogen fuel as a promising potential enabler for green aviation can play as the cryogenic cooling medium, the hurdles in hydrogen, the need for auxiliary equipment for safe handling, and the related add-on weight, complexity, and cost make this technology not still ready to be used but require more research and development as outlined in the paper. Besides, phase change materials, currently suggested for batteries and electrical machines, seem to play a greater role in addressing the cooling challenges in HEP systems in the near future. There is a potential for PCM to be integrated with active cooling techniques to shape an effective, lightweight and safe thermal management system.

As another promising emerging technology, the additive manufacturing technique has the potential to solve the problem of compact, complex, and lightweight heat exchangers that can dissipate the high amount of waste heat from the rather high heat-generating elements even in a centralized cooling system.

As a final remark, the cooling methods outlined for each TMS component in the present research must undergo assessment within the ultimate hybrid electric propulsion arrangement to guarantee secure operations that align with aviation standards and mandates. Additionally, there is a necessity to revise aviation standards for HEP based on established instances from tests and simulations. Consequently, a thorough safety analysis becomes an essential facet of technology advancement, requiring heightened attention for TMS, an aspect that is presently not extensively emphasized. Finally, given that most of the emerging cooling technologies, reviewed in this article, are still in the developmental stages, particularly in addressing associated challenges, the related standard and certification processes can be developed in parallel using the simulations and prototypes. The certification processes that engage both regulatory bodies, e.g. FAA and EASA, and technology developers and researchers, would expedite the practical implementation of such technologies in the context of achieving low-emission aviation.

Abbreviations	
AC	Alternating Current
ANPC	Active-neutral-point-clamped
BTMS	Battery Thermal Management System
DC	Direct Current
EASA	European Union Aviation Safety Agency
ECS	Environmental Control System
ESS	Energy Storage System
EV	Electric Vehicle
FAA	Federal Aviation Administration
FC	Fuel Cell
FCML	Flying Capacitor Multilevel
HEP	Hybrid Electric Propulsion
HEX	Heat Exchanger
HT-PEMFC	High-Temperature Polymer Electrolyte Membrane Fuel Cell
HTC	Heat Transfer Coefficient
LIBs	Lithium-ion batteries
LT-PEMFC	Low-Temperature Polymer Electrolyte Membrane Fuel Cell
MEA	More Electric Aviation
NPC	Neutral-point-clamped
OEW	Operating Empty Weight
PA-PBI	Phosphoric-Acid Dopped Polybenzimidazole
PCM	Phase Change Materials
PE	Power Electronics
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PFSA	Perflurosulphonic Acid
PMSM	Permanent Magnet Synchronous Motor
SOFC	Solid Oxide Fuel Cell
TEC	Thermoelectric Cooling
TMS	Thermal Management System
TRL	Technology Readiness Level
VCS	Vapor Compression
WBG	Wide-bandgap

CRediT authorship contribution statement

Majid Asli: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Paul König:** Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Dikshant Sharma:** Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Evangelia Pontika:** Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Jon Huete:** Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Karunakar Reddy Konda:** Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Akilan Mathiazhagan:** Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Tianxiao Xie:** Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Klaus Höschler:** Funding acquisition, Supervision. **Panagiotis Laskaridis:** Funding acquisition, Supervision.

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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