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Evaluation of heat transfer technologies for high temperature polymer electrolyte membrane fuel cells as primary power source in a regional aircraft

Friedrich Franke[1] · **Antje Link**[1] · **Stefan Kazula**[1]

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Abstract

High-temperature proton exchange membrane fuel cells (HT-PEM FCs) represent a promising avenue for generating carbon dioxide-free electricity through the utilization of hydrogen fuel. These systems present numerous advantages and challenges for mobile applications, positioning them as pivotal technologies for the realization of emission-free regional aircraft. Efficient thermal management of such fuel cell-powered systems is crucial for ensuring the safe and durable operation of the aircraft, while concurrently optimizing system volume, mass and minimizing parasitic energy consumption. This paper presents four distinct heat transfer principles tailored for the FC-system of a conceptual hydrogen-electric regional aircraft, exemplified by DLR's H2ELECTRA. The outlined approaches encompass conductive cooling, air cooling, liquid cooling, phase change cooling and also included is the utilization of liquid hydrogen as a heat sink. Approaches are introduced with schematic cooling architectures, followed by a comprehensive evaluation of their feasibility within the proposed drivetrain. Essential criteria pertinent to airborne applications are evaluated to ascertain the efficacy of each thermal management strategy. The following criteria are selected for evaluation: safety, ease of integration, reliability and life-cycle costs, technology readiness and development as well as performance, which is comprised of heat transfer, weight, volume and parasitic power consumption. Of the presented cooling methods, two emerged to be functionally suitable for the application in MW-scale aircraft applications at their current state of the art: liquid cooling utilizing water under high pressure or other thermal carrier liquids and phase-change cooling. Air cooling and conductive cooling have a high potential due to their reduced system complexity and mass, but additional studies investigating effects at architecture level in large-scale fuel cell stacks are needed to increase performance levels. These potentially suitable heat transfer technologies warrant further investigation to assess their potential for complexity and weight reduction in the aircraft drivetrain.

Keywords HT-PEM FC · Hydrogen-electric aircraft · Thermal management · Heat pipe

List of Symbols

$\Delta \dot{h}_{prod.}$	Specific enthalpy flow of products	$\frac{J}{kg\,s}$
$\Delta \dot{h}_{reac.}$	Specific enthalpy flow of reactants	$\frac{J}{kg\,s}$
P_{el}	Electrical power	W
R_T	Technology benefit rating value	
w_c	Weighting factor for criterion evaluation	

Abbreviations

ATAG	Air traffic action group
PGS	Pyrolytic graphite sheets
PHP	Pulsating heat pipe
SoA	State of the art
TLAR	Top level aircraft requirements
TMS	Thermal management system
TPG	Thermal pyrolytic graphite
TRL	Technology readiness level
BPP	Bipolar plate
DLR	German Aerospace Center
FC	Fuel cell
HHV	Higher heating value
HT-PEM	High temperature-polymer electrolyte membrane
LT-PEM	Low Temperature-polymer electrolyte membrane
MEA	Membrane electrode assembly
MTBF	Mean time between failure
PBI	Polybenzimediazole

✉ Friedrich Franke
friedrich.franke@dlr.de

[1] Institute of Electrified Aero Engines, German Aerospace Center (DLR), Lieberoser Straße 13a, Cottbus, Germany

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1 Introduction

The decarbonization of the aviation industry stands as one of the central technological challenges of the 21st century. In line with this urgency, the European Commission's Flightpath 2050 report has set forth an ambitious objective: to reduce carbon dioxide emissions in the aviation sector by 75% until 2050 [1]. In response to this goal, both the Air Traffic Action Group (ATAG) and the German Aerospace Center (DLR) have devised comprehensive strategies aimed at realizing this emission reduction. An important part of these strategies is the introduction of all-electrical and hybrid-electrical aircraft in the regional mission range [2, 3].

Two proposed examples for fuel cell based hybrid-electric propulsion in regional aircraft are the H2ELECTRA of the DLR (see Fig. 1) and ZEROAVIA's ZA2000 [4].

The H2ELECTRA, a conceptual aircraft under development by the Institute of Electrified Aero Engines at the DLR, serves dual roles as a platform for comparative analysis of hydrogen-based electric propulsion and as a technological showcase for the feasibility of such aircraft. Engineered to fulfill the specifications typical for a regional aircraft, including a passenger capacity of 50, a cruise speed of 170 ms^{-1}, and a range of up to 1000 nautical miles (1852 km), the H2ELECTRA's design is driven by the Top Level Aircraft Requirements (TLAR) [5].

The selection of a suitable FC technology was guided by a comparative examination of various fuel cell technologies and their suitability for airborne applications, considering the special requirements arising due to application in aviation systems. For application in the H2ELECTRA, HT-PEM FCs were selected due to their high potential for application in aviation [6].

In recent years, there has been a growing interest in HT-PEM FCs as a promising avenue for generating carbon-emission-free electricity through the utilization of hydrogen fuel.

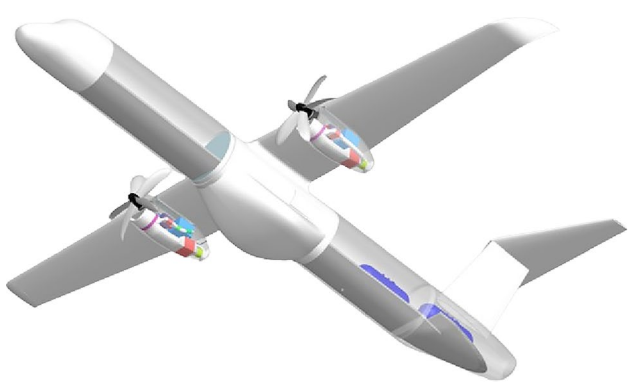

Fig. 1 Design Concept: H2ELECTRA, Nacelle - integrated Propulsion System Reproduced with Permission from [5]

These fuel cells typically utilize a phosphoric acid-doped membrane composed of polybenzimidazoles (PBIs) and are designed to operate at temperatures reaching up to 200°C [7]. Despite exhibiting marginally lower power densities on cell level compared to low-temperature PEM-FCs, HT-PEM FCs offer a multitude of advantages over their counterparts [8, 9]. These include:

- Improved reaction kinetics [10],
- Elimination of humidification system [11],
- Structural integrity [11],
- No buildup of liquid water at cathode [7] and
- Larger ΔT to environment facilitates cooling [7, 10, 12].

The increase of operational temperatures notably diminishes the mass and bulk of the thermal management system (TMS). Nevertheless, it remains crucial to devise a TMS capable of consistently maintaining the fuel cell system at optimal operating temperatures. Concurrently, it is essential to minimize system mass, volume, and power consumption to increase the overall specific power and volumetric power density of the drive train.

2 Heat generation and transfer in HT-PEM FCs

Contemporary, state of the art HT-PEM FC systems achieve efficiencies of $\eta_{FC} = 40 - 50\%$ [4, 13]. However, a significant fraction of the reaction's electrochemical potential, given by the higher heating value (HHV), is not transformed into electrical power P_{el}. This remaining energy dissipates as heat.

$$\eta_{FC} = \frac{P_{el}}{\Delta H_0^{HHV}} \tag{1}$$

In Low - Temperature Proton Exchange Membrane (LT-PEM FCs) the primary sources contributing to heat generation, along with their respective contributions, are well known. These include the entropic heat of the reaction (55%), irreversible heat stemming from electrochemical reactions (35%), and Joule heating due to Ohmic resistance (10%) [14, 15].

At cell level, the entropic heat of reaction and the irreversible heat of reaction are generated within the catalyst layers of the FC, at the point where the chemical reactions occur. Ohmic heating on the other hand arises wherever electrical charge is transported and is inversely proportional to the electrical conductivity of the traversed material. Consequently, Ohmic heating within the ion-conducting membrane and the catalyst layers is relatively high, whereas heat generation in the bipolar plates is negligible due to their high conductivity [16, 17].

Local variations in heat generation are also evident between the anode and cathode catalyst layers owing to the different chemical reactions occurring on each side: hydrogen oxidation at the anode and oxygen reduction and water formation at the cathode. Nonetheless, given their close spatial proximity and the significantly elevated heat levels compared to the other parts of the fuel cell, it is assumed for the remainder of this overview that the entirety of the heat is generated uniformly within the membrane electrode assembly (MEA). The components and of a basic fuel cell alongside the basis of heat generation are depicted in figure 2.

Although similar studies, which specifically address the precise localization of heat sources in HT-PEM FCs are currently absent from the authors' knowledge, it is assumed that the distribution of heat sources in HT-PEM FCs aligns with the distribution, observed in low temperature configurations, because of their analogous operational principles [12, 18].

The heat that is generated in the MEA needs to be transferred out of the center of the stack (internal) and on to the environment (external) via the three fundamental mechanisms of heat transfer: conduction, convection and radiation. A portion of this heat is removed in this manner by the product mass flow exiting through the cathode and anode outlet. The remaining excess heat Q_{Ex}, which must be removed by the TMS to retain an isothermal operating condition in the FC-Stack is given by:

$$\dot{Q}_{Ex} = \sum \Delta \dot{h}_{Re} - \sum \Delta \dot{h}_{Pr} - P_{el} - \dot{Q}_R - \dot{Q}_{Cd} - \dot{Q}_{Cv} \qquad (2)$$

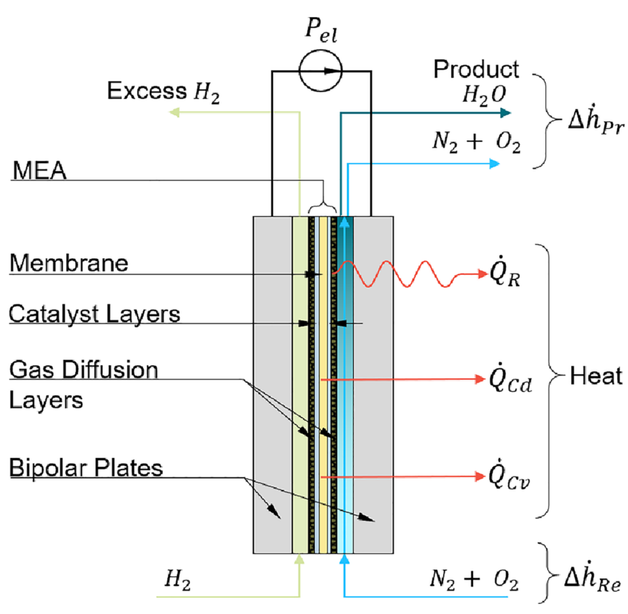

Fig. 2 Components and heat transfer of a fuel cell

Where Δh_{Re}, Δh_{Pr} correspond to the specific enthalpies of the reactants and products of the reaction and P_{el} represents the electrical power, which is output by the cell. The heat that is transferred from the cell is composed of the radiation $\dot{Q}_R$, the conduction $\dot{Q}_{Cd}$ and the natural convection $\dot{Q}_{Cv}$ to the environment.

Various technological solutions exist that apply combinations of these heat transfer mechanisms to dissipate excess heat. Subsequent sections introduce these technologies as well as requirements, which are relevant for their integration into an aircraft powertrain.

2.1 Heat flux calculation for regional aircraft

The amount of heat that needs to be dissipated by the TMS of the FC is essential for the evaluation of applicable heat transfer technologies. To determine the heat fluxes, a model of the H2ELECTRA was developed, derived from preliminary design studies. A configuration with **6** nacelles and a respective maximum propulsive shaft power of 491kW for each propeller was selected. A preliminary design of the drive train resulted in a hybrid system, where batteries provide additional power during load peaks. To determine the load distribution between the FC and the battery system, it was divided into six mission phases with different total and partial electric power requirements: take-off, climb, cruise, descent, loiter and final approach. During take-off and initial climb, the battery systems was sized to provide 250kW for a short period of time. As a consequence of this hybridization of power sources, the FC system has a peak power output of 530kW and is operated for better efficiency at 400kW during the cruise phase [5],

Based on fundamental fuel cell modeling and manufacturer data [4], the heat load that must be rejected by the TMS, after accounting for the cooling effect of fuel heating is 265kW at peak load.

3 Heat transfer technologies

Heat transfer technologies for FC-Stacks are categorized into four distinct groups based on operating principles to remove the heat from the fuel cell stack, as seen in Fig. 3. The different operating principles are presented along with the variations that exist within each group. Existing literature and studies on each of these categories are summarized and the current state of research as well as future potential for each operating principle is laid out.

3.1 Conductive cooling

For the scope of this overview, conductive transfer technologies for TMSs are defined as systems that rely on

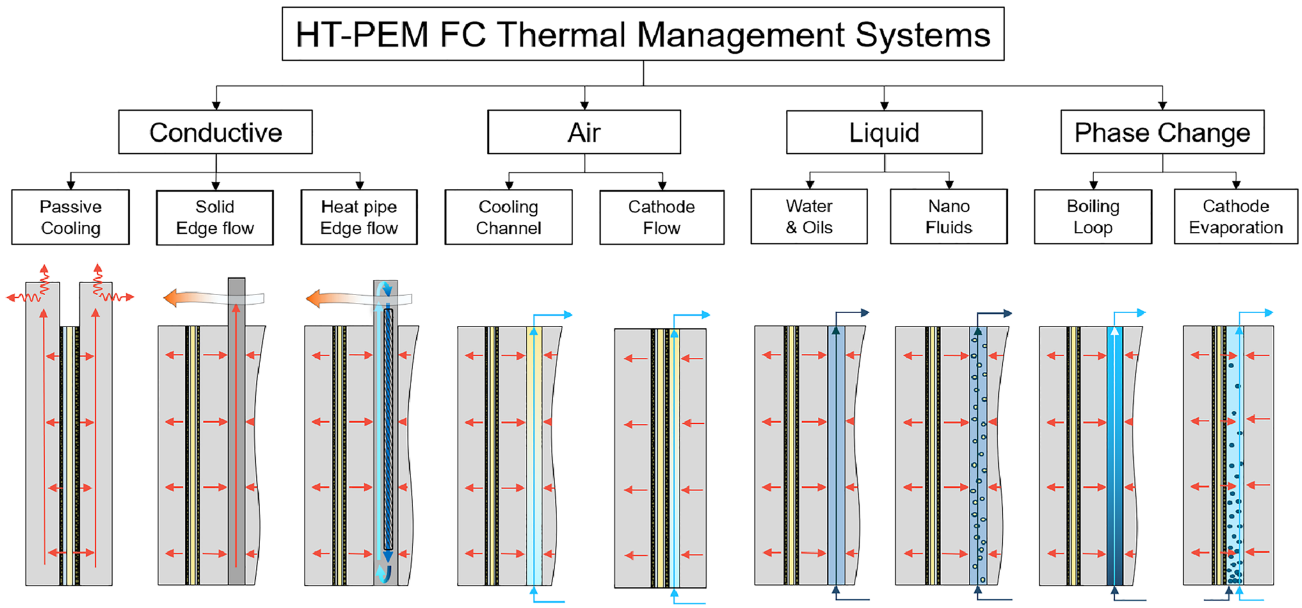

Fig. 3 Categorization of HT-PEM FC heat transfer technologies

conduction rather than the active circulation of fluids to dissipate heat from the MEAs in the center of the stack. Conductive systems can be further categorized into passive and edge-flow cooled as illustrated in Fig. 3. In passive systems, like the examples depicted in Fig. 3a, no fluid flow is imposed at the edge of the cells and therefore these systems only rely on natural convection, conduction and radiation to remove heat from the FC system. This approach eliminates the need for additional coolant pumps, ducts fans and valves, potentially reducing system complexity and mass, but is severely limited with regard to the amount of heat that can be rejected across the stack boundary.

Edge-cooled systems on the other hand use forced convection via imposed fluid flow at the edges of the fuel cell stack. Such systems are depicted in Fig. 3b and c.

Both approaches absorb heat from the MEA and conductively transfer it to the edge of the FC stack. This transfer is facilitated by either the bipolar plates themselves or by incorporating additional highly conductive elements that are inserted in between individual FCs or at the ends of FC stacks. The effectiveness of these thermal management approaches is therefore closely related to the thermal conductivity of the conducting heat spreaders as well as the distance over which the heat needs to be transported.

Hence, as the stack size increases, conductive cooling becomes increasingly challenging. This difficulty arises as well, because the boundary area available for heat dissipation via radiation or natural convection increases at a slower rate than the volume of the stack and the generated heat [19].

3.1.1 Solid heat spreaders

Burke et al. [20] conducted investigations on the technological potential of conductive TMS for fuel cell systems and concluded that in order for this approach to be applicable, the heat transmission distance needs to be very small $< 10cm$ and the conductivity of the heat spreader needs to exceed $1000 \mathrm{Wm^{-1}K^{-1}}$. Given these requirements, the study suggests potential system weight decreases of up to 50% through the implementation of conductive systems.

A number of technological solutions that demonstrate thermal conductivity above the threshold given by Burke et al. are listed in Table 1.

Wen et al. [26] applied pyrolytic graphite sheets (PGS) for the thermal management of a single LT-PEM fuel cell in a passive heat spreader configuration (see Fig. 3b), resulting in reduced temperature, a decreased temperature gradient through the cell and increased current density for certain operating points.

Building on these results, further studies [27, 28] demonstrate effective cooling of small FC stacks (≈180W) using

Table 1 Thermal conductivity of various technologies

Technology	Conductivity in $[\mathrm{Wm^{-1}K^{-1}}]$
Thermal Pyrolytic Graphite (TPG)	≈ 1500 [21]
Pyrolytic Graphite Sheets (PGS)	≈ 1800 [22]
Cylindrical Heat Pipes	≈ 1700 [23]
Flattened Heat Pipes	≈ 7000 [24]
Planar Heat Pipe	≈ 14 000 - 20 000 [25]

integrated PGS that were cut to fit the flow channels and included fins to dissipate the heat to the environment. For these studies, passive as well as edge-flow cooled systems, employing a variety of fans were investigated. All systems achieve temperature homogenization and system mass reduction in varying degrees, but systems using larger fans for edge-cooling require a significant measure of parasitic power.

Achieving homogenous temperatures within the stack as well as across a singular cell is beneficial to achieve a more uniform current density resulting in higher power output and better degradation behavior [12, 29, 30, p.106], [31, p.97], [32, p.353].

Wang et al. [33] performed numerical analysis on conductive thermal management approaches for HT-PEM FCs. Different composite heat spreaders, combining copper with PGS and TPG were investigated in an edge-cooled configuration. Parameter studies on heat spreader thickness and fin lengths were conducted demonstrating effective cooling of the MEA with maximum temperature differences of 5.85K, for 1mm PGS thickness and 2.76K for 1mm of TPG.

For a comparative analysis, the same FC system was also simulated with thermal oil cooling (see Sect. 3.3). Depending on coolant mass flow, the oil system reached temperature differences ranging from 5.6K to 11.6K. To achieve temperature homogeneity on par with TPG, the pressure drop in the coolant flow channels requires parasitic pump power exceeding the electrical power generated by the cell. It is to be noted however that for the conductive approaches in this study, the thermal boundary condition at the ends of the heat spreader fins was set to be equal to ambient temperatures. This results in an ideal external heat sink and might lead to too optimistic performance results in the simulations.

3.1.2 Heat pipes

Another way to achieve high thermal conductivity is the integration of heat pipes (see Fig. 3c). While the working principle of a heat pipe is not based on conduction, but on the phase change of a working fluid, the closed system as a whole can be considered as a thermal conductor and is therefore classified as a conductive TMS.

Vasiliev [34] introduced the implementation of various types of heat pipes into the TMS of fuel cell stacks. Firat et al. [23] investigated the feasibility of cooling a 1000W HT-PEM FC stack by inserting miniature cylindrical heat pipes into specially designed Bipolar Plates (BPPs). Stable temperatures with a maximum temperature gradient of $\Delta T \approx$ 20K across the stack were achieved for a configuration of 6 heat pipes per cell.

Oro et al. [35] conducted analytical and experimental studies on flattened heat pipes with micro grooves providing capillary pumping and deionized water as a working fluid. The study examined the feasibility of integrating these devices into the flow plates of LT-PEM FCs to maintain operating temperatures. Heat transfer rates of 1.8W cm^{-2} were demonstrated, meeting the requirements for operating conditions.

Studies for heat pipes in HT-PEM FC stacks were executed by Sasiwimonlit et al. [24] for flattened heat pipes with air-edge flow and Supra et al. [31] for cylindrical heat pipes, that were embedded in designated cooling layers between each third cell and externally cooled with water-edge flow. Both studies included the successful heating of the stack during start-up, as the heat transfer direction in the heat pipes is reversible.

The studies concluded, that heat pipe technology is a suitable and promising technology for the thermal management of HT-PEM FCs.

To improve specific power of the system and reduce the stack volume, Wang et al. [36] developed an array of micro-heat pipes with an aluminum casing, that can be integrated into the bipolar plates of a LT-PEM FC stack. The condenser side of the pipes extended beyond the stack boundary and was fitted with serrated fins to facilitate the air-flow edge cooling. An improvement in specific power of 12.2% and power density by 9.5% was measured when comparing to conventional air cooling as described in section 3.2.

Flat-plate heat pipes, also called vapor chambers or planar heat pipes, present a different realization of the same underlying heat transfer principle of closed loop evaporation and condensation. Studies by Burke et al. [20, 25] and Huang et al. [37, 38] demonstrate successful temperature control and temperature uniformity for small fuel cell stacks, while decreasing system weight compared to conventional liquid cooling.

Another implementation is the pulsating heat pump (PHP), sometimes also referred to as an oscillating heat pipe. Unlike the aforementioned heat pipes, the pulsating heat pipe does not depend on the capillary forces of a wick to transport fluids. Instead, it leverages the geometry of thin flow channels and the natural surface tension of the working fluid. This design creates vapor-fluid plugs within the channels, facilitating the transfer of mass and heat between the evaporation and condensation ends of the device through pressure differentials in the flow channel [39].

A number of studies have evaluated the potential of PHP for LT-PEM FC cooling. Chang et al. [40] studied a variety of working fluids, reaching an heat flux of 1.47W cm^{-2} with a 5:1 methanol-deionized water mixture, which meets requirements for heat dissipation of the FC at 80°C. Min et al. [41] compared PHP cooling with traditional air and liquid cooling using CFD. It was determined that the heat pipe solution is on par with liquid cooling and far surpassing air cooling in both temperature reduction as well as temperature uniformity.

3.1.3 Challenges of conductive systems

While conductive TMS offer large potential for the improvement of HT-PEM FCs, there also exists a number of drawbacks and challenges that can arise due to their implementation:

- **Increased stack volume**; due to the additional conductive elements that need to be inserted in between cells, the volume of the stack increases. Current research is conducted to integrate heat pipes into the bipolar plates and thereby mitigate the volume increase to some extent [42].
- **Increased internal electrical resistance**; the heat spreader elements introduce additional Ohmic resistance into the stack, which leads to voltage and therefore power loss across the fuel cell. While this can be mitigated to a certain degree by choosing highly conductive materials or applying surface treatments to reduce contact resistance, the overall performance decreases [36, 37].
- **Limited scalability**; all of the investigations mentioned above refer to stacks with relatively small active cell areas. Because the potential of heat conduction is closely related to the traversed distance, future studies need to demonstrate feasibility in larger cells.
- **Limited regulation capability**; because of the passive nature of the conductive elements, the heat transport within the stack cannot be varied during operation and can only be controlled in the edge-flow configurations by adjusting the external heat sink.
- **Complexity and cost**; despite numerous scientific studies on the conductive cooling of HT-PEM FCs, the manufacturing of these systems remains restricted to small-scale prototypes. While the removal of active systems could potentially enhance reliability and reduce operational costs over time, the intricate and innovative nature of the technology is accompanied by significant manufacturing expenses and the need for technology maturation.
- **Gravity dependency**; another factor that has to be taken into account when integrating heat pipes into airborne systems, is the influence of the direction of gravity onto the TMS. This occurs, because capillary pumping effectiveness of the wick structure inside the heat pipe varies when coinciding with or opposing gravity, as shown by Huang et al. [37].

3.2 Air cooling

In air cooling systems, the heat is transported from the MEA via forced convection of an air mass flow. Such systems can be divided into three categories:

The first is the cathode flow method, depicted in Fig. 4a where the cooling air flow is the same as the reactant air flow at the cathode and has the dual functions of providing oxygen for the reaction as well as absorbing and dissipating heat. The advantage of this approach is the simplicity and very small number of added systems. This in turn has the potential to reduce stack size and weight [43].

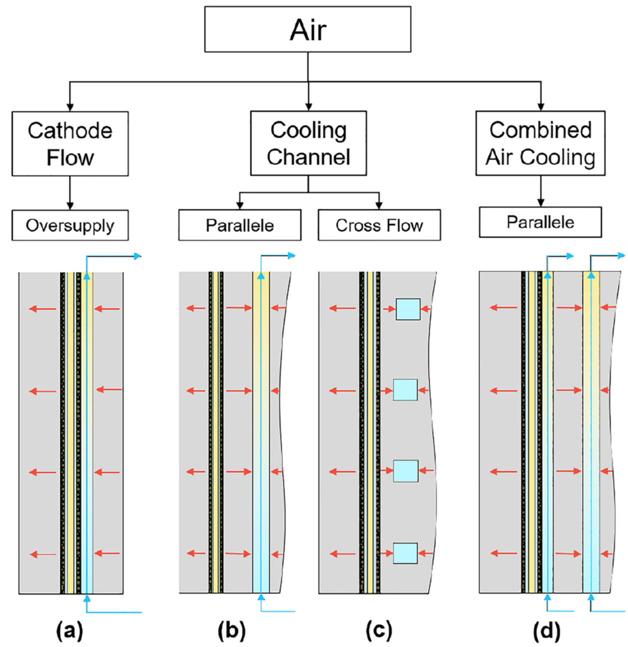

Fig. 4 Selected schematics of air-based TMS; Cathode-side air oversupply (**a**), sing additional cooling channels (**b**, **c**) and combined Approach (**d**)

Heras et al. [44] developed such a cathode flow TMS for a LT-PEM fuel stack and investigated different air flow configurations with regard to their thermal management performance and resulting FC power output. In the given study the stack temperature was successfully controlled at optimal operating temperature, but the different fan configurations consumed between 30% and 50% of the consumed Hydrogen's energy due to the pressure drop imposed by the flow through the oxidizer/cooling channels.

The application of cathode flow thermal management for HT-PEM systems was studied by Kurz et al. [45] for stacks with 90W. For the small stack, temperature control was achieved using a singular fan with variable speeds and a PI controller. In the cathode flow configuration, the change of the air intake also directly influences the reaction rate due to the different amount of oxygen at the cathode. Temperature differences increase as the airflow increased and reached up to 17.5K across the stack, but stable operation was still ensured in all operating points.

Andreasen et al. [46] also investigated the thermal management using the cathode flow method for a stack with an electrical power of 400W and demonstrated successful operation, while also noting the challenge of large temperature differences across singular cells as well as across the entire stack.

The second way to use air flow for fuel cell cooling is to integrate separate cooling channels into the bipolar plates. Channels can be parallel to the reactant flow as depicted in Fig. 4b, perpendicular (Fig. 4c) or have other geometries.

This method enables the regulation of the temperature without influencing reaction stoichiometry, but also necessitates the integration of an additional air management system including blowers and channels. Separate air cooling has been researched by a number of studies for low - temperature [47, 48] as well as high - temperature [49] PEM FCs. The temperature differentials and parasitic power requirement, if provided in the respective studies, are cataloged in Table 4 within Appendix A.

The third option, depicted in Fig. 4d, is combined air cooling, which uses the concepts of a cathode air oversupply together with additional air-filled cooling channels. This approach provides a larger aerodynamic cross-section enabling a lower pressure drop, while maintaining a constant mass flow, which in turn causes less parasitic power consumption. Furthermore, it is still possible to rely on a singular air-system keeping the simplicity high and the number of parts low. This method provides the most heat rejection of all air cooled systems and is frequently used, especially for smaller power sizes [31, 49]. Demonstrations of combined air cooling were, among others, executed by Barreras et al. [50] and Reddy et al. [49].

3.2.1 Challenges of air cooling

- **Large coolant mass flow**; due to the comparatively low heat capacity of air, the specific amount of heat, that is absorbed by the coolant air flow is low, which necessitates a large mass flow to achieve sufficient heat flux. This large mass flow is the reason for a number of the following challenges.
- **Parasitic power**; the air flow through the cathode channels or the designated cooling channels needs significant amounts of power to provide the required pressure differential. This power demand for ventilation increases drastically with stack size.
- **Temperature gradients**; as the air heats up along the cooling channel the convective heat flow from the MEA decreases. This results in a temperature gradient along the channel length, which can impede stable and durable operation [51]. Further increasing the air flow only partially increases performance, because the cooling efficiency deteriorates with increasing mass flow [52].
- **Induced aerodynamic drag**; a larger airflow than for the heat exchangers in liquid or conductively cooled systems must be supplied to the FC-system by the environment, facilitated by a scoop on the exterior of the aircraft or alternative inlets. This additional airflow induces further drag on the aircraft.

3.3 Liquid cooling

Liquid cooling is the predominantly used heat transfer technology for fuel cell stacks in power classes above 5kW [53]. This preference stems from the superior specific heat capacity of liquids compared to gases, facilitating more efficient heat transfer through convection [31, 54]. As shown by previous studies, this choice ensures good controllability and uniform temperature distribution across the fuel cell [55, 56]. It also enables the utilization of waste heat in other subsystems in the aircraft that require thermal energy, such as de-icing systems, fuel conditioning units, or cabin heating. The use of a hot liquid as the cooling medium facilitates the transfer of waste heat to these subsystems. This results in the combined utilization of both the heat and power generated by the fuel cell system [57]. For LT-PEM FCs the fluid, used for thermal management usually is deionized water, which is pumped through designated channels in the bipolar plates or separate cooling cells, where it heats up. Subsequently, the liquid is chilled back down to lower temperatures in a liquid-air heat exchanger and then fed back to the stack in a closed-loop cycle.

For HT-PEM FCs on the other hand, the operating temperature range poses a challenge for water cooling, because of the boiling point of water under standard atmospheric pressure conditions. This phase change may also be used as an intended cooling system, as is laid out in the subsequent section 3.4. For liquid cooling however, boiling is detrimental to the control of the system and creates local instabilities [58, 31, p. 8]. Hence, liquid-based TMS either operate the system under high-pressure to ensure the water remains liquid, or employ other fluids such as thermal oils [51, 59] or nanofluids [60].

Nanofluids are fluids that have nano-sized solid particles like aluminum oxide Al_2O_3 suspended in the base fluid. This enhances the thermal conductivity of the fluid and has proven to achieve greater convective heat transport [61, 62]. Studies have shown that by leveraging this increased heat transfer, the size of the TMS and the heat exchanger specifically could be reduced by up to 21% [63]. While the heat transfer increases with the insertion of nano particles, the dynamic viscosity also increases. This results in a higher pressure drop and more required pumping power [64, 65].

3.3.1 Challenges of liquid cooling

Liquid cooling represents the state of the art for large FC systems and therefore numerous studies are conducted to improve this operating principle with regards to reliability and efficiency [56, 66, 67]. Nonetheless, a few challenges remain, which might impede the integration into a regional aircraft's power train.

- **Coolant leakage**; if coolant leaks into the MEA or neighboring systems, as observed by Supra et al. [31], the performance of the stack can decrease drastically and the membrane can be permanently damaged [68]. This decreases the safety and reliability of the system and simultaneously increases the difficulty of maintenance.
- **Number of parts**; the liquid coolant cycle extends beyond the stack itself and includes a number of necessary components to operate, each of which presents a possible point of failure as well as additional system weight. These parts are: the coolant lines, the pumps, valves, deionizing filter, coolant reservoir and heat exchanger with a complementary fan.
- **Parasitic power**; the pumps and the blower of the heat exchanger consume power, which lessens the overall efficiency.
- **Weight**; the number of components as well as the coolant fluid itself increase the weight and volume of the fuel cell system considerably [69].

3.4 Phase change cooling

For phase change cooling, the coolant transitions from the liquid into the gaseous state as it passes through the stack. This approach offers superior heat transfer compared to liquid cooling because it harnesses the latent heat of evaporation in addition to the specific heat capacity of the coolant fluid [19, 54]. The concept of phase change cooling can be implemented in various ways: Goebel [70] proposed an architecture, which uses wicking in the reactant channels on the cathode side to transport liquid coolant to the MEA. The liquid evaporates, thereby absorbing waste heat and is then expelled through the cathode outlet together with the product water and excess air.

Another approach is the closed loop boiling and condensation cycle as implemented by a number of researchers [55, 71–73]. In this setup, the liquid coolant is evaporated in designated channels in the stack. The resulting gas is then cooled in a condenser, where it returns to the liquid state and can be fed back to the beginning of the cooling loop. The advantage of this system in comparison to liquid cooling is the smaller required fluid flow, which in turn leads to lower system mass and parasitic power consumption. Furthermore, the area of the condensing heat exchanger can be smaller, which decreases the drag caused by the air intake [55].

A study by Song et al. [74] proposes a pumpless phase change TMS for a HT-PEM FC stack, eliminating the need for a supplementary coolant pump. Instead, the pumping power is supplied by the buoyancy difference of the liquid and vapor phase. The steam rises to a condensing heat exchanger that is placed above the stack. The condensed water flows back to the reservoir located below and closes the cycle. This setup achieved small temperature differences across the stack (6K) and managed to keep the stack within operating temperature range.

Another method, that has been applied for LT-PEMs is the injection of coolant droplets into the cathode-side air stream as depicted in figure 3*i*. With this approach the TMS also provides the necessary humidification for the membrane [75, 76]. The heat dissipation of this approach is restricted however, due to the limited amount of water, that can be evaporated in the cathode channels before flooding occurs. This prevents cathode injection from being a stand-alone thermal management system in low temperature fuel cells.

The application of phase change cooling in HT-PEM is particularly promising, because the elevated operating temperature range beyond $100°C$ facilitates heat transfer and enables the usage of water as a coolant in boiling loop architectures.

3.4.1 Challenges of phase change cooling

While phase change-based thermal management for HT-PEM fuel cells provides excellent heat transfer, a number of factors impede the widespread implementation into fuel cell systems, especially for aviation purposes.

- **Regulation and control**; within the domain of boiling flow cooling, the initiation of nucleate boiling triggers sudden changes in both pressure and heat transfer within the channel, posing challenges for precise prediction. Consequently, this phenomenon results in limited control over the thermal conditions of the fuel cell stack [31]. Additionally, the critical heat flux denotes a crucial threshold. Beyond this point, temperatures escalate rapidly due to diminished heat transfer to the coolant. This reduction arises from the onset of an alternate heat transfer mechanism, primarily induced by the predominance of the coolant in its gaseous state. This phenomenon can lead to a form of thermal runaway as heat transfer diminishes with rising temperatures [73].
- **Coolant leakage**; similar to liquid cooling, the possibility of coolant leakage into the active area of the fuel cells poses a problem to the long term operation of phase change TMS.
- **Number of parts**; nucleate boiling architectures include many parts which increase the mass and complexity of the system and present multiple points of failure. These include the pumps, the boiling channels, the condensing radiator and a water separator each of which is essential for the operation of the system.

3.5 Hydrogen heat sink

The H2ELECTRA [5], a conceptual hydrogen electric aircraft, uses cryogenic liquid hydrogen, which is stored at a temperature of about 20K, as its main energy source. One approach to remove heat from the fuel cell stack is to use this stored hydrogen as a local heat sink.

The heat sink can be integrated into the fuel cell system in a number of different ways one of which is the open ended fuel conditioning approach. In this case, the liquid hydrogen fuel acts as the coolant in an open ended phase change TMS by being conducted along channels in or close to the stack before being diverted to the anode as a reactant.

This way the hydrogen leverages its latent ΔH_{lat} and sensible heat ΔH_{sens} to absorb a share of the waste heat of the fuel cell, while also being brought to a state which is fit for utilization in the chemical reaction. It is to be noted however that only a fraction $f = 6\%$ of the generated heat can be rejected in this way as shown in equation (3).

$$f = \frac{\Delta H_{lat} + \Delta H_{sens}}{\Delta H_0^{HHV} \cdot (1 - \eta_{FC}) \cdot FU} \approx 0.06 \tag{3}$$

where ΔH_0^{HHV} is the higher heating value of hydrogen, ΔH_{lat} the latent heat of evaporation, ΔH_{sens} the sensible heat of the fluid, η_{FC} the electrical efficiency of the fuel cell, assumed to be 50%, FU the fuel utilization (90%) and f the fraction of the heat that can be absorbed by the cryogenic fuel.

Accordingly, although ongoing developments in cryogenic fuel management such as active fuel conditioning aim to improve hydrogen's cooling effectiveness, its theoretical capacity remains limited. Therefore, hydrogen cooling can only be considered as a supplemental method for managing heat in the FC stack.

In Addition, it is noted that, while hydrogen as a heat sink offers only limited potential for FC waste heat rejection, its cryogenic temperature makes it a promising candidate for cooling electrical subsystems such as inverters and electric machines. These components produce less thermal load compared to the fuel cell stack and can benefit from lower operating temperatures in terms of efficiency and lifetime. Therefore, using hydrogen cooling in this context may offer a more practical and effective application pathway.

3.6 Combined cooling architectures

Beyond the aforementioned thermal management approaches, there also exists the possibility to combine different architectures to provide sufficient cooling. Zhao et al. [77] combined a conductive cooling approach with separate-channel air cooling as well as cathode oversupply to investigate the behavior of a short stack of LT-PEM FCs. It was concluded, that the combination achieved higher temperature uniformity as well reduced parasitic power consumption when compared to the purely air cooled system.

Combining different TMS provides many opportunities for optimization and enables design considerations tailored to specific requirements like the mission envelope of a regional aircraft. This also results in the possibility to balance redundancy with performance and other integration constraints. However, it also results in the increase of complexity and introduces a larger number of systems, which present possible points of failure and therefore may reduce reliability and safety.

Of particular interest are combinations which can provide high heat transfer for a short time to alleviate load peaks. One example of such an approach is the addition of an evaporation cooling system to an underlying air or liquid-based main system. If the evaporation system is only used during high load phases like takeoff and climb, the dimensions of the main cooling system could be drastically reduced. This results in a smaller primary as well as secondary TMS achieving an overall weight loss and efficiency gain for the cooling system.

As outlined in Sect. 3.5, employing the cryogenic hydrogen fuel is another possible approach of combining cooling architectures. Because the hydrogen needs to be conditioned to FC temperature in order to minimize thermal stresses and ensure efficient operation, using the fuel as a heat sink is an effective proposition.

A third combination approach, which is also the simplest to implement, involves cathode air cooling in tandem with any of the other seven architectures. This method does not require additional cooling systems. Instead, it only requires adapting the oxidizer system to supply overstoichiometric cathode air. This adaptation also enables temperature regulation of the entire fuel cell stack.

4 Evaluation of heat transfer technologies

The primary functional requirement for the TMS is the capability to maintain the fuel cells within the operating temperature range, which typically is in between 160°C -180°C for HT-PEM FCs. However, many additional characteristics need to be considered when determining a systems efficacy for aviation. In this overview, the technical properties of each thermal management approach are categorized based on their influence on five criteria, which were selected by a group of aerospace engineers to evaluate a system's suitability for integration into an aircraft. The criteria are listed and further explained below.

4.1 Performance (P)

The primary performance metric of a TMS is its potential *heat transfer* from the MEA to the environment to maintain the cell at the desired temperature. This is the fundamental requirement for the system. Consequently, other advantages of an architecture are inconsequential if this requirement is not met. In addition to heat rejection, it is crucial to consider the *temperature uniformity* of the stack. Temperature gradients within a single cell and between cells should be minimized to enhance fuel cell power output and reduce degradation.

Most TMS consume power, thereby reducing the specific power of the entire fuel cell system. Thus, *parasitic power consumption* is accounted for when evaluating a system's performance. These performance metrics are assessed concerning the *weight* and *volume* of the architectures, as reducing the power train's mass and volume is a core challenge in developing a hydrogen electric aircraft. Therefore, a system that provides excellent temperature management but increases the total mass may not be viable for a regional aircraft.

Table 4 in the appendix provides a detailed overview of recent studies comparing the selected metrics of performance. This comparison functions as a baseline for the summarized evaluation, that is executed later in this chapter and summarized in Table 5.

4.2 Ease of integration (I)

Ease of integration describes the expenditure and challenges as well as potential benefits that arise from the integration of the TMS into the aircraft. To assess the ease of integration, the architectures are evaluated with regard to a number of aspects:

Temperature regulation capability measures how quickly and accurately the system can react to inputs and adapt the fuel cell stack temperature. It is especially investigated if the heating, which is required for the cold start of a HT-PEM FC can be supplied, without adversely affecting operations or damaging the cells. Throughout an aircraft's mission the power demand fluctuates strongly. This also results in a variable power output of the fuel cell and therefore necessitates variable heat rejection of the TMS. These changing heat rates are further influenced by the changing environmental conditions that also impact the heat rejection capability. Additionally, it is also investigated if the respective TMS provide *cold-start capability*, which is essential for routine operation of the fuel cell system between flight cycles.

If additional components like special casings or air ducts are needed to integrate the TMS into the aircraft, the ease of integration is decreased and the enclosed volume increased. An assessment is conducted to estimate the *induced drag* the systems cause by either enlarging the enclosed volume or necessitating air intakes.

Different systems interact with each other, especially if they are mounted in close proximity. These resulting interactions of the cooling architectures with other systems are evaluated as *synergies with surrounding components*.

The degree of fulfillment of the different TMS architectures for matters of integration is detailed in Table 6.

4.3 Safety (S)

Safety is an essential criterion for any system, which is to be integrated into an airplane. It is defined as a state, where the risk of an incident occurring is lower than a set threshold [78, p.706]. The safety of a given TMS is determined by assessing following characteristics:

The magnitude of inherent risks describes the probability of faults, that exist because of the principle of the TMS itself, e.g., high pressure gas buildup in boiling loop systems. Furthermore, its *behavior in case of malfunction* is categorized to gauge the danger, arising due to a systems failure modes. Exemplary for his concept: For many air-based architectures leakage can result in the mixture of coolant air with reactant hydrogen leading to imminent flammability and thereby increasing the danger beyond the inherent risk due to uncontrolled fire or explosions.

Possibility of redundancy refers to the availability of backup systems or components that can take over in the event of a failure. A TMS with high redundancy will have multiple layers of safety, reducing the likelihood of a complete system failure. For instance, having multiple blowers or independent cooling loops can enhance the system's resilience.

The impact of a system failure on the aircraft and its occupants is evaluated by the *severity of failure*. Failures are categorized from "minor effect on aircraft operation" to "catastrophic", which may result in loss of life and the destruction of the aircraft [78, p.706]. For the assessment of safety criteria it is referred to able 7.

4.4 Reliability and life-cycle cost (R)

The reliability of a system denotes how frequently it is expected to fail. An important metric to quantify reliability is the mean time between failure (MTBF) [78, p.707].

A system that has a large *number of parts* is more likely to fail and therefore have a smaller MTBF, because every functional component presents a possible point of failure. Besides the number of components, the *complexity* of a given system or component is a key factor, which is used to evaluate the reliability of a TMS. A lower complexity relates to a higher rating in overview Table 8, which summarizes the evaluation.

The reliability of a system also strongly influences its operating cost, as frequent part replacements and maintenance are expensive in their own right and furthermore ground the aircraft. Maintenance, together with the *cost of manufacturing* and *cost of disposal* is summarized in the life-cycle costs, which are crucial properties for the evaluation of any technological system.

In order to assess the life cycle costs of the various TMS, it is also taken into account whether the system is more likely to fail, because of degradation or aviation-specific environmental influences, like vibrations, pressure changes or contamination through volcanic ash. Furthermore, it is considered if monitoring of the individual components is possible to predict certain failure states and thereby decrease maintenance cost and enhance safety.

4.5 Technology readiness and development (T)

The Technology Readiness Level (TRL) is used to rate the maturity of a technology. It starts with level 1, which corresponds to the basic working principles being reported and goes up to 9, which means the system is successfully employed in mission operations [79, p.11]. The higher the TRL is, the more likely an implementation into an aircraft is in the near future, because aviation systems have to be diligently tried, tested and certified. A combination of industrial applications and research projects is listed in table 9 along with references to the projects from which the given TRL was derived [76, 80–82]. For the selected evaluations the TRL was given for a stationary application unless a amendment is added in the table, which specifies airborne application

For this evaluation the TRL is assessed alongside the *prospects of development*, which take into account possible breakthroughs in the respective field of technology as well as their potential impact on the application in thermal management. The difficulty for advancement of a technology is given via the *research gap*.

4.6 Fulfillment of criteria

The extent to which the criteria are met is assessed on a scale from 1 to 5, with 1 indicating that the criterion is not met at all and 5 indicating excellent fulfillment, thereby indicating high suitability for aircraft application. Each of the 5 Criteria is further comprised of a set of properties as described in Sects. 4.1–4.5. These properties are then assessed from very negative **(- -)** to very positive **(+ +)**. This property evaluation at fundamental level is carried out in various ways: Whenever possible, it is based on available data from the industry or published scientific literature as is the case for some performance-based properties summarized in the appendix Table 4. However, many of the presented technologies are still in the early phases of research, leading to a lack of data, which inhibits the extrapolation of quantitative data for larger power requirements or more fully developed and integrated systems. Therefore, for most properties a qualitative system analysis was executed and in some cases simplified thermal and mathematical modeling was applied. All fundamental property assessments are summarized in criteria fulfillment overview Tables 5–8. The tables include estimations of property importance and a rationale for the given evaluation. The final degree of fulfillment is calculated by a weighted sum of the properties and given at the bottom row of each table.

The degree of fulfillment is subsequently illustrated for each TMS approach in Fig. 5.

It is noteworthy that passive cooling systems achieve the highest ratings in terms of safety (S) and reliability (R). However, the values for performance (P) and technological

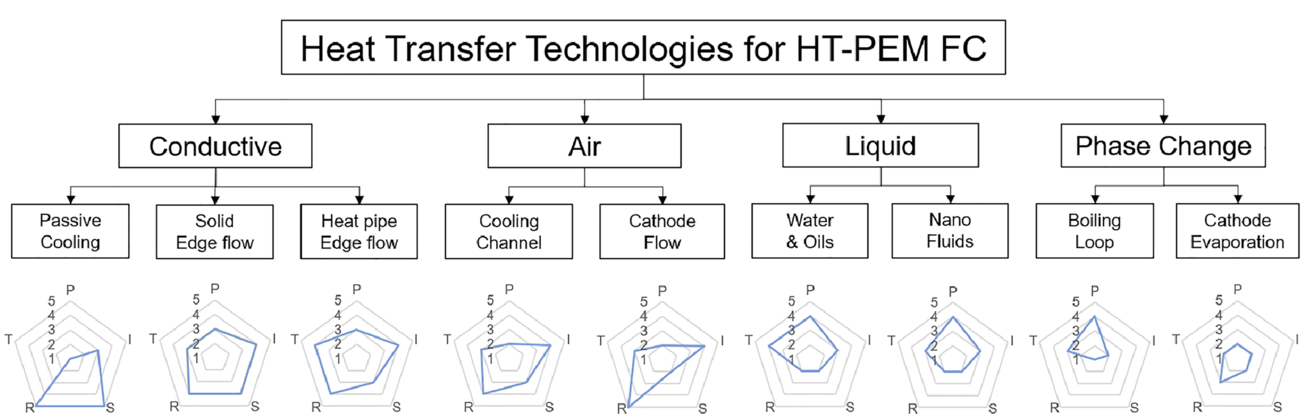

Fig. 5 Evaluation of Selected Criteria Fulfillment of Different Heat Transfer Technologies. Evaluated Criteria Are Performance (P), Ease of Integration (I), Safety (S), Reliability and Life-cycle Costs (R), Technology Readiness and Development (T); Fulfillment Is Rated from 1 - Unsuited for Aviation to 5 - Very Well Suited

development (T) are the lowest. This disparity can be attributed to the inherent physical limitations, which were explained in the previous chapter and the lack of significant anticipated improvements in the foreseeable future.

Edge flow systems, incorporating solid heat spreaders or heat pipes, demonstrate good overall ratings, but achieve only a neutral performance value. Air cooling methods show similar ratings to conductive methods but exhibit even lower performance.

At the other end of the spectrum, liquid cooling architectures and the boiling loop exhibit very high performance levels. However, these systems are deficient in other critical categories. In particular, the boiling loop shows significant shortcomings in safety and reliability, receiving the lowest ratings in these areas. The low ratings are mainly attributed to the great number of dependent parts and possible points of failure in the liquid and phase change systems, which can impede the operation of a whole stack or even the entire system.

The disparity between these high-performance architectures and the more reliable, safer, and easier-to-integrate systems is clearly evident in the shapes of the plots depicted in Fig. 5. Additional, detailed assessments, which analyze the various aspects, that make up each of the evaluation categories are executed in tabular form and included in the appendix.

4.7 Benefit analysis

The five evaluation criteria are not of equal importance for the efficacy of a TMS in an aircraft. To determine the relative importance of each category, a pairwise comparison of the metrics is presented in Table 2.

Based on this comparison, a weighing factor w_c is calculated, which quantifies the significance of each evaluation criterion. The inclusion of weighting enables more nuanced analysis of the presented architectures [83].

Performance emerges the most important evaluation metric with a relative weighting factor of 0.4, followed by safety with 0.3. The remaining three criteria achieve notably lower relative weights.

Furthermore, the performance metric is especially crucial as it imposes a threshold; a thermal management system must meet the fundamental requirement of sufficient heat rejection to be considered functional.

Due to this performance threshold, passive TMS are not a viable option, despite their good ratings in safety and reliability. The heat transfer capacity of passive-edge systems is orders of magnitude too small to adequately cool megawatt-level systems [49], such as those envisioned for the H2ELECTRA. Consequently, passive systems are excluded from further analysis in this overview.

The weighting of the criteria is employed to generate an encompassing technology rating of the TMS architectures combining the fulfillment of the criteria with their respective weights. The resulting ratings (R_t) are calculated using Eq. 4, where k represents the number of investigated criteria and $d_{c,t}$ the degree of fulfillment of the criteria c by the respective technology t. The resulting ratings are comprised in Table 3.

Table 2 Criteria Weighting Table; Values: Row criterion is more important than Column Criterion = 2, equally important = 1, less important = 0

Criteria	P	I	S	R	T	w_c
Performance (P)	-	2	2	2	2	0.40
Ease of integration (I)	0	-	0	0	1	0.05
Safety (S)	0	2	-	2	2	0.30
Reliability and Life-cycle cost (R)	0	2	0	-	1	0.15
Technology Readiness and development (T)	0	1	0	1	-	0.10

Table 3 Weighted rating R_t and degree of Fulfillment $d_{c,t}$ of heat transfer technologies

Criteria (c)	P	I	S	R	T	R_t
weighting(w_c)	0.4	0.05	0.3	0.15	0.1	–
Conductive material (d_1)	3	4	4	4	3	3.5
Heat pipes (d_2)	3	4	3	4	4	3.3
Designated air channel, (d_3)	2	4	3	4	3	2.8
Cathode flow, (d_4)	2	4	2	5	3	2.7
Water, Oil, Glycol, (d_5)	4	3	2	2	4	3.1
Nano fluids, (d_6)	4	3	2	2	3	3.0
Boiling loop, (d_7)	4	2	1	1	3	2.5
Evaporation cooling, (d_8)	2	2	2	3	2	2.2

$$R_t = \sum_{c=1}^{k} w_c \cdot d_{c,t} \tag{4}$$

Current state-of-the-art conductive and air cooling techniques, like passive systems, have not demonstrated sufficient performance for reliable implementation in large-scale FC systems. However, while advancements in passive cooling architectures are improbable, these methodologies have shown performance improvements in recent years. Ongoing research across multiple fields aims to further enhance the heat transfer capabilities of these cooling strategies.

Due to the compromise between moderate performance and high reliability and safety, as well as prospects for future development, conductive systems with solid heat spreaders and heat pipes achieve the highest weighted ratings in the benefit analysis, with scores of 3.5 and 3.3, respectively. These scores assume the coupling with environmental air as an external heat sink.

Closest in rating are liquid cooling with conventional thermal carrier fluids (3.1) or nano fluids (3.0). Liquid cooling is the only approach that is widely implemented for FC systems with a high power output and is therefore the most extensively researched and has the highest TRL, but at the same time provides fewer avenues for significant advancement. The integration of nano fluids may enhance performance, but their influence on fuel cell operation is yet to be determined as well as the resulting system complexity investigated.

Boiling loop phase change systems on the other hand, achieve the best performance in theory, but the architecture lacks detailed studies and implementations. Its complexity and inherent operational risks also pose a challenge for aircraft implementation, which results in the comparatively low rating of 2.5.

4.8 Uncertainty and bias

Given the method of qualitative rating in this paper, the authors acknowledge the possible impact which rating errors may have on the results of this research. Because of the large number of subject areas covered in this overview, ratings on the fulfillment and importance of the selected criteria can diverge between analysts and depend on the personal background of the evaluating engineers and scientist. While this approach enables a broad coverage and general assessment of the topic of HT-PEM cooling in aviation, it is also influenced by subjective bias which each assessor may hold. These potential biases should be taken into account when considering the results of this research. In addition, further research is currently under way to quantify the claims and ratings put forth in this paper, and reaffirm certain assertions with conclusive and objective data.

5 Conclusion

A comprehensive evaluation of cooling methods for HT-PEM fuel cells intended as primary power sources in regional aircraft was conducted. The suitability was assessed using the weighted criteria of performance (P), ease of integration (I), safety (S), reliability and life-cycle cost (R) as well as technology readiness and potential development (T).

Liquid cooling represents the state of the art for large FC systems, because of its high heat rejection capability and is currently the only widely implemented TMS architecture for high power demand. However, this study identifies a number of challenges, which may impede the integration of liquid-based TMS into a regional aircraft power train.

A central challenge is the large weight and necessary integration volume of the many auxiliary subsystems of a liquid coolant cycle, like the heat exchanger, the pumps, the reservoir and the coolant itself. This large number of integral parts also presents multiple points of failure, which significantly decreases the reliability and safety of the system and therefore necessitates many layers of redundancy to ensure operational safety. These additional redundant systems further increase the volume and weight and this in turn makes the investigation of alternative cooling architectures a worthwhile endeavor.

Among the methods presented, the boiling-loop system, which utilizes cyclical phase changes of a coolant, demonstrates the best performance. However, it encounters the similar issues to those of the liquid system. Additionally, the complexity of the heat transfer mechanisms and the challenges associated with managing two-phase flow pose significant concerns for the controllability and reliability of the system. Consequently, this technology is not deemed viable at this stage. Substantial advancements in understanding the operation beyond the point of the critical heat transfer and significant improvements in the TRL through demonstrators and field tests are required before it can be considered a feasible option.

Air cooling methods, either using the cathode side reactant supply or designated air channels, also achieve low ratings due to deficits in performance and the large amount of consumed parasitic power for providing sufficient air flow. The cathode flow method however has the potential to be used as a nnn TMS in combined cooling architectures.

Conductive cooling methods with imposed flow at the edges of the stack emerged as the methodologies with the highest weighted ratings. Highly conductive materials as well as heat pipes provide superior ease of integration due to their simple operating principle and increase reliability because the number of parts in the cooling system can be significantly reduced. Systems with solid heat spreaders are particularly resistant to malfunctions, because a single faulty element only decreases performance and does not hinder the operation of the surrounding cooling system or the fuel cell operation.

Although the scalability of conductive systems remains uncertain and improvements in specific heat rejection are required to enable implementation in high-power systems, this technology presents the most promising alternative to conventional liquid cooling. This approach could prove especially advantageous for aviation, because of the elevated significance of weight, safety and reliability in airborne applications.

Therefore, novel concepts need to be developed to effectively integrate conductive heat transfer technologies into high power fuel cell systems and increase the overall specific power of fuel cell driven powertrains. Such an increase in performance will aid in extending the range for hydrogen electric aircraft and can contribute to achieving carbon free regional air traffic.

Appendix A: Evaluation overview

Table 4 Performance references of PEM TMS

TMS type	FC type	Power	ΔT_{cell}	ΔT_{stack}	Parasitic Power	Specific power
Conductive, heat spreader; [33]	HT-PEM	single cell	6.7K	–	–	–
Conductive, heat spreader, edge flow [28]	LT-PEM	183W		–	2.1%	18.5W kg^{-1}
Conductive, heat pipe, passive; [84]	LT-PEM	single cell	15K	–	0	–
Conductive, Heat pipe, edge-flow; [31](p.68ff)	HT-PEM	575W	5.6K	10.7K	< 10%	–
Air, Cathode Flow; [44]	LT-PEM	2500W	–	1.3K	50%	211.5W kg^{-1}
Air, Cathode Flow; [45]	HT-PEM	90W	10.4K	17.5K	≈ 50%	40.9W kg^{-1}
Air cooled, separate channel; [31]	HT-PEM	669W	25.3K	14.8K	≈ 10%	–
Air cooled, separate channel; [47]	LT-PEM	2300W	≈10K	20.57K	–	–
Air cooled, separate channel; [48]	LT-PEM	800W	5K	8K	–	–
Air cooled, separate channel; [52]	LT-PEM	500W	4K	–	–	158W kg^{-1}
Combined air: separate Channel and Cathode flow [49]	HT-PEM	1000W	20K	50K	–	–
Combined air: separate Channel and Cathode flow [50]	HT-PEM	1500W	–	–	14%	–
Liquid, Water; [84]	LT-PEM	single cell	18K	–	–	–
Liquid, Water; [85]	LT-PEM	225W	≈15K	–	–	–
Liquid, Water; [86]	LT-PEM	1000W	≈9.57K	–	–	–
Liquid, Water; [87]	LT-PEM	70000W	–	–	–	283W kg^{-1}
Liquid, Fragoltherm S-15-A; [31](p.39ff)	HT-PEM	782W	9.9K	–	< 10%	–
Phase Change, Boiling; [74]	HT-PEM	1000W	6K	6K	0 %	–
Phase Change, Evaporation; [76]	LT-PEM	108W	–	–	–	–

Table 5 Performance (P) Evaluation Overview; (–) corresponds to very bad fulfillment, (-) bad, (o) neutral, (+) good, (++) very good

Criteria			Criteria definitions	Conductive Cooling			Air Cooling		Liquid Cooling		Phase change cooling	
				Passive	Conductive material (Edge flow)	Heat pipes (Edge flow)	Designated channel	Cathode flow	Water, Oil, Glycol	Nano fluids	Boiling loop	Cathode Evaporation
Performance (P)	**Performance (P)**	(w = 0.4)	Heat transfer (5) Temperature uniformity (2) Parasitic power consumption (3) Aviation environment impact on performance (Vibration, pressure, humidity, ash, g-force etc.) (2)	(–) Not sufficient for medium or larger stack [Reddy.2014] (–) Large differences across stacks with large cell area (++) No parasitic power (o) Unchanged	(-) Better than passive, not demonstrated for large stacks [Ramezanizadeh.2019] (o) Good for small active area (+) Comparatively low blower power (o) Performance drop due to low pressure, performance gain for humidity	(-) Better than mono material [Burke.2009] (+) [Supra.2014] (+) Edge cooling power not well documented (+) Often used in space applications	(-) Not demonstrated for stacks above 3kW (–) Large differences along channel (-) Large pressure drop and blower power (o) Performance drop due to low pressure, performance gain for humidity	(-) Not suitable as singular TMS for large stacks (–) Differences along channel (-) Large pressure drop and blower power (o) Performance drop due to additional air filtration needed for cathode intake	(++) State of the art for high power stacks (+) Medium difference along cell, low differences across stack (-) Pump and blower for heat exchanger required (o) Simiar performance in airborne environment	(++) Higher heat transfer than other coolants (+)Medium temperature difference along cell, low differences across stack (–) More pumping power required due to higher viscosity (o) Similar performance in airborne environment	(++) Higher heat transfer than liquid cooling (++) Temperature uniformity across stack (+) Smaller pump and condenser-blower required, experimental investigations into gravity driven pump. (o)	(–) Not sufficient heat rejection for medium or larger stacks, [Hwang.2016] humidification for HT-PEM not required (o) Increase in uniformity (+) Capillary effect can be used for coolant supply (-) High intake humidity lowers performance
				(–)	**(o)**	**(o)**	(-)	(-)	(+)	(+)	(+ +)	(-)

Table 5 (continued)

Criteria		Criteria definitions	Conductive Cooling			Air Cooling		Liquid Cooling		Phase change cooling	
			Passive	Conductive material (Edge flow)	Heat pipes (Edge flow)	Designated channel	Cathode flow	Water, Oil, Glycol	Nano fluids	Boiling loop	Cathode Evaporation
Weight (W)	(w = 0.4)	Low specific system weight (4) Low system volume (3)	(++) No additional components (++) No additional components	(+) No additional heat exchanger, coolant pipe and reservoir (+) No additional heat exchanger, coolant pipe and reservoir	(o) Heavier than mono material, no additional heat exchanger, coolant pipe and reservoir (+) No additional heat exchanger, coolant pipe and reservoir	(+) No heat exchanger, no added components between cells (+) No heat exchanger loop needed	(+) No need for coolant cycle and heat exchanger. Only larger compressor needed (++) More compact since no room for additional channels is needed	(-) Added weight from coolant cycle (-)Added space from coolant cycle	(–) Added weight from coolant cycle (-) Added space from coolant cycle	(o) Added weight from coolant boiling and condensation cycle, but less than liquid cooling system (-) Added space from phase change cycle	(o) Added weight if water is recaptured in condenser and water separator, otherwise light system (o) Moderate space requirement because of steam handling systems
			(+ +)	**(+)**	**(+)**	**(o)**	**(o)**	**(-)**	**(-)**	**(-)**	**(o)**
		RESULT	**1**	**3**	**3**	**2**	**2**	**4**	**4**	**4**	**2**

Table 6 Ease of Integration (I) Evaluation Overview; (- -) corresponds to very bad fulfillment, (-) bad, (o) neutral, (+) good, (++) very good

Criteria		Criteria definitions	Conductive Cooling			Air Cooling		Liquid Cooling		Phase change cooling	
			Passive	Conductive material (Edge flow)	Heat pipes (Edge flow)	Designated channel	Cathode flow	Water, Oil, Glycol	Nano fluids	Boiling loop	Cathode Evaporation
Ease of integration (I)	(w = 0.05)	Temperature regulation capability (4) Necessity for additional components, e.g., casing, ducts, fire wall (5) Synergies with surrounding components (3) Induced drag (4) Integration volume (3) Cold start capability (2)	(–) No control possible (++) (–) No controlled mass or heat flux, that could be used (++) No drag besides the added aircraft volume (++) Small compact unit (-) Necessity for heat pads in the stack; external heat pads would lead to high temperature differences	(o) Regulation via change of edge flow, Internal control not possible. Long response times due to thermal inertia [Scholta.2009] (+) Ducts and fins needed, if edge flow employs air, liquid edge cooling increases number of components (+) Hot exhaust: de-icing, cabin heat, fuel conditioning, driving turbine (o) Induced drag for necessary edge flow (++) Compact unit and air ducts (+) Heat pads can be placed at heat spreader fins [Flückiger.2007]	(+) Regulation via change of edge flow, passive internal control via heat pipe design [Vasiliev.2009] (+) Ducts and fins needed, if edge flow employs air, liquid edge cooling increases number of components (+) Hot exhaust: de-icing, cabin heat, fuel conditioning, driving turbine (o) Induced drag for necessary edge flow (+) Less compact unit and air ducts (+) Heat pads can be placed at heat spreader fins [Flückiger.2007]	(++)Airflow can be regulated to establish control (+) Additional ducts, fins and blower needed (+) Hot exhaust: de-icing, cabin heat, fuel conditioning, driving turbine (o) Induced drag for cooling channel air flow (+) Less compact unit and air ducts (o) Heating units can be placed at cooling channel inlets to provide fast start-up capability, but inducing large temperature differences along the channel. [Andreasen.2008]	(+) Airflow can be regulated to establish control, but fuel cell behavior and stoichiometry cannot be regulated independently from the TMS (+) Air supply system for cathode intake can be enlarged and adapted. Filter system needed to not contaminate the cathode (+) Large air oversupply can impact fuel cell performance, Hot exhaust: de-icing, cabin heat, fuel conditioning, driving turbine (o) Induced drag for air flow intake (+) Very compact, because channels are already integrated into the stack (o) Heating units can be placed at cooling channel inlets to provide fast start-up capability, but inducing large temperature differences. [Andreasen.2008]	(++) Regulation via changing coolant flow rate (-) Coolant lines, reservoir, cooling blocks if channels are not integrated in BPPs, pumps, heat exchanger, deionizing unit for water cooling (+) Hot liquid: de-icing, cabin heat, fuel conditioning (o) Induced drag from airflow through the coolant heat exchanger (-) Large system with many distributed components require large integration volume (o) Heating can be achieved through cooling channel, gas channel and reaction heating to achieve acceptable start-up times with homogeneous temperature distributions [Wang.2014]	(++) Regulation via changing coolant flow rate (-) Coolant lines, reservoir, cooling blocks if channels are not integrated in BPPs, pumps, heat exchanger (-) Interaction and electrical resistance of nano particles with fuel cell, hot liquid: de-icing, cabin heat, fuel conditioning (+) Less induced drag from heat exchanger air (-) Large system with many distributed components require large integration volume flow because of smaller needed HEX size [Islam.2016] (o) Heating can be achieved through cooling channel, gas channel and reaction heating to achieve acceptable start-up times with homogeneous temperature distributions	(-) Difficult regulation due to complex two phase flow, unstable point of critical heat flux [Huang.2022] (o) Similar components to the components of a liquid cooling loop, but the required flow rate is much smaller decreasing system volume (o) Heat of the coolant difficult to utilize due to complex flow and need for controlled condensation (+) Less induced drag because of smaller needed condensing heat exchanger [Kösters.2022] (+) Smaller integration volume due to less needed coolant flow (-) Requires more supplemental heating energy for channel heating, alternatively increasing stack bulk with electrical heat pads	(-) Control via capillaries difficult, droplet injection not freely scalable (o) Few components if open cycle is used (capillary, injector), more on closed loop (water separator, feedback lines) (-) Moist air in Cathode exhaust channel hard to utilize, for HT-PEM no humidification necessary (+) Only marginal increase in drag, since no large air flows are required (o) TMS can be integrated closely with the reactant system, but water separator and coolant lines for circulation in closed cycle increase volume
			(o)	(+)	(+)	(+)	(+)	**(o)**	**(o)**	(-)	(-)
		RESULT	**3**	**4**	**4**	**4**	**4**	**3**	**3**	**2**	**2**

Table 7 Safety (S) Evaluation Overview; (–) corresponds to very bad fulfillment, (-) bad, (o) neutral, (+) good, (++) very good

Criteria		Criteria definitions	Conductive Cooling			Air Cooling		Liquid Cooling		Phase change cooling	
			Passive	Conductive material (Edge flow)	Heat pipes (Edge flow)	Designated channel	Cathode flow	Water, Oil, Glycol	Nano fluids	Boiling loop	Cathode Evaporation
Safety (S)	(w = 0.3)	Inherent risks e.g., circuit shortage, fire, rapid depressurization (4) Behavior in caes of malfunction, e.g., leakage of dangerous fluid (3) Consequences of failure (5) Possibility for redundancy (2) Severity of failure (4)	(+) Possible short circuit if heat spreaders are electrically conductive (+) For breaking of fins: small particles in FC environment (+) Overheating of neighboring cells (o) Redundant fuel cells, TMS redundancy via multiple heat spreaders per active cell (++) Even in failure, system still conducts residual heat. Conduction increases as overheating occurs	(o) Risks depend on conductive material, possible short circuit for conducting materials (-) broken material and debris spread through edge flow and might damage or impede systems downstream (o) Failure of conductive unit: overheating of neighboring cells, failure of flow: overheating of all affected stacks (+) Multiple blowers, TMS redundancy via multiple heat spreaders per active cell (+) In case of failure the system still conducts residual heat, conduction increases as overheating occurs	(+) No particular inherent risk (-) Leaks of working fluid in heat pipe can lead to short circuits, degradation of membranes, if heat pipes are integrated into BPP, possibility of contact with reactant hydrogen resulting in flammability (-) Failure of single conductive unit: overheating of neighboring cells, contamination of membranes possible, For failure of edge flow: overheating of stack, electrical conductivity of cell compromised (+) Multiple blowers, TMS redundancy via multiple heat spreaders per active cell (-) Rapid decrease in conductivity and heat rejection if leakage in heat pipe occurs	(+) No particular inherent risk (-) In case of air contamination due to filter failure: Cooling channels contaminated, debris in channels has potential to destroy cell, leakage to exterior can lead to contact with reactant hydrogen and flammability (-) Overheating of entire stack, which is supplied by faulty air management unit (o) Possibility of multiple blowers supplying the channels, single channels redundancy by design. Loss of single channel results in only slight decrease in operability (o) Quick overheating of fuel cell, large loss of generated power and possible damage to the fuel cell if not shut down	(+) No particular inherent risk (–) Malfunction in cooling system also affects reactant supply, contamination or particles in air flow can cause damage to membrane, which can lead to direct contact with hydrogen and flammability (–) Instant power loss of fuel cell system (o) Multiple air supply systems and filters, also serves as redundancy for FC-reactant supply (–) Complete loss of power	(-) Glycols are possibly toxic (-) Leakage of toxic fluids dangerous, possible short circuit, damage to membrane and contamination of surrounding systems (-) Overheating of stack, possible power decrease or loss, in case of pump failure: boiling and pressure buildup in cooling system (-) Multiple coolant loops, that need to be operable separately (-) Ranges from small performance decrease to total inoperability of stack and loss of power: Minor to complete loss of power	(+) No particular inherent risk (-) Leakage of nanofluids dangerous, possible short circuit, damage to membrane and contamination of surrounding systems (-) Overheating of stack, possible power decrease or loss, in case of pump failure: boiling and pressure buildup in cooling system (-) Multiple coolant loops, that need to be operable separately (-) Ranges from performance decrease to total inoperability of stack and loss of power: Minor to complete loss of power	(-) High pressure gas buildup (–) High pressure hot gas released into proximity, short circuits, structural damage (-) Overheating, power decrease or loss, damaging of neighboring systems (-) Separate boiling-condensation loops, that need to operable independently (–) Major to complete loss of power	(+) No inherent risk (-) Dryout of wick, or flooding of cathode, release of hot vapor (-) In case of dryout wick (if used) can become fire hazard, faulty injection leads to flooding and power loss, possible damage to cathode air supply system (-) Integration restrictions of injector/wick because of limited space (-) Slight performance decrease to power loss: Minor to complete loss of power
			(+ +)	(+)	**(o)**	**(o)**	**(-)**	**(-)**	**(-)**	**(–)**	**(-)**
		RESULT	**5**	**4**	**3**	**3**	**2**	**2**	**2**	**1**	**2**

Table 8 Reliability and Life-cycle costs (R) Evaluation Overview; (–) corresponds to very bad fulfillment, (-) bad, (o) neutral, (+) good, (++) very good

Criteria			Criteria definitions	Conductive Cooling			Air Cooling		Liquid Cooling		Phase change cooling	
				Passive	Conductive material (Edge flow)	Heat pipes (Edge flow)	Designated channel	Cathode flow	Water, Oil, Glycol	Nano fluids	Boiling loop	Cathode Evaporation
Reliability and Life-cycle cost (R)	**Reliability**	(w = 0.15)	Number of parts (5) Complexity (4) Failure because of aviation-specific environment, e.g., pressure, vibration, ash (2) MTBF (Estimate) (4)	(++) Very low number of additional parts (++) Very low (++) Robust system (++) Few points of failure	(+) Heat spreaders, blower, air filter (debris, ash), temperature sensors, control unit, heat pads (++) Airducts and fins, regulation via blower speed possible [las Heras.2018] (o) Low pressure environment, airborne contaminants and high ambient temperature on runway present challenges [Las Heras.2018] (+) Simple system, structure needs to be developed for aircraft environment, simple blower redundancy achievable, MTBF for heat spreaders not known but assumed to be high	(+) Heat pipes or vapor chambers, blower, air filter (debris, ash), temperature sensors, control unit, heat pads (+) Airducts and fins, regulation via blower speed possible [las Heras.2018] (o) Low pressure environment, airborne contaminants and high ambient temperature on runway present challenges (+) Heat pipes demonstrated resilience in space applications [SOA.2023] MTBF for different types of heat pipes not known	(+) Blower, air ducts, manifolds, air filter, temperature sensor, control unit, air heater (++) Very simple system (+) Obstruction of channels through contaminants possible, high resilience to mechanical stresses (+) Few components and simple redundancy	(++) Integration into fuel management system leads to part reduction, blower/ compressor manifolds, air filter, air ducts, control unit air heater (+) Simple system, but conditioning of larger air flow important (o) Contamination of air flow more detrimental, because of direct impact on fuel cell performance (++) Very few components, redundancy can be coupled with fuel system	(-) Many dependent parts, coolant lines, pump, blower, heat exchanger, valves, de-ionizing filter, coolant channels, control system, heating pads (-) Complex system with many points of failure (+) Debris and contaminants can inhibit heat exchanger functionality (-) Many components with non-negligible failure rates, redundancy only possible in parts	(-) Many dependent parts, coolant lines, pump, blower, heat exchanger, valves, de-ionizing filter, coolant channels, control system, heating pads (–) Complex, unproven system with many points of failure (+) Debris and contaminants can inhibit heat exchanger functionality (–) Many components with non-negligible failure rates, redundancy only possible in parts, impact of nanofluids on MTBF of fluid management system not well known	(–) Very many dependent parts, coolant lines, reservoir, boiling cooling channels, condensing heat exchanger, water separator, blower, air ducts, air filter, pressure regulating valves, control unit, heating pads (–) Very complex system with many points of failure, critical operating points, unproven system (o) Damage to condensing heat exchanger through debris possible, behavior of boiling loop changing with environmental pressure (–) Many components with non-negligible failure rates, redundancy only possible in parts, influence of two-phase system on MTBF not well known	(o) Intermediate number of dependent parts, coolant reservoir, wick/ injection, water separator (o) Moderate complexity of subsystems (+) Not susceptible to aviation based influences (+) Few active components, reliant on air management subsystem
				(+ +)	(+)	(+)	(+)	(+ +)	(-)	(-)	(–)	**(o)**

Table 8 (continued)

Criteria			Criteria definitions	Conductive Cooling			Air Cooling		Liquid Cooling		Phase change cooling	
				Passive	Conductive material (Edge flow)	Heat pipes (Edge flow)	Designated channel	Cathode flow	Water, Oil, Glycol	Nano fluids	Boiling loop	Cathode Evaporation
	Costs	(w = 0.15)	Manufacturing (4) Maintenance & monitoring (3) Degradation (5) Disposal/ Recycling (1)	(+) Conductive elements can be expensive (+) Few parts to monitor and exchange, replacement of single conductive elements difficult (+) Conductive elements consistent over time (+) Few elements to recycle, conductive elements can be safely disposed of	(0) Complex stack assembly, expensive materials, but simple system integration (+) Stacks can be exchanged easily, without disrupting a coolant cycle, conductive units either between cells, facilitating maintenance or integrated into BPP, fault detection through visual inspection and thermal disturbance (++) Minimal to no decrease of thermal conductivity through lifetime (o) Monomaterial (PGS) can be safely disposed of, recycling difficult	(-) Very complicated stack assembly, expensive TMS parts, simple system integration (+) Stacks can be exchanged easily, without disrupting a coolant cycle, conductive units either between cells, facilitating maintenance or integrated into BPP, Fault detection through visual inspection and thermal disturbance) (o) Decrease of heat pipe conductivity over time [Hassan.2017] (+) Casing of heat pipe can be recycled, internal structure and wick safely disposed	(+) Integration of channels in BPP not challenging, manifold and airduct integration are simple (o) Blower, filter and ducts maintained easily, monitoring and clearing of channels difficult. (+) Blower performance consistent over time, leakage and contaminant of channel buildup over time (++) Only blower as added component for disposal/ recycling	(++) Simpler stack geometry (o) Exchange of TMS elements closely coupled with cell maintenance, blower and duct maintenance simple (+) Performance of TMS over time consistent, but FC performance might decrease due to contaminants in MEA (++) Only blower as added component for disposal/ recycling	(+) Complex system, but comparatively cheap of the shelf parts (-) Difficult maintenance and exchange of parts within the coolant loop, leakage into neighboring systems possible (+) Performance of TMS mostly consistent over time, losses due to coolant leakage and filter degradation (o) Many systems to dispose, recycling of some parts and material possible	(-) Complex system, special parts for handling of nanofluids (-) Difficult maintenance and exchange of parts within the coolant loop, leakage into neighboring systems possible (+) Performance of TMS mostly consistant over time, losses due to coolant leakage and filter degradation (-) Many systems to dispose, recycling of some parts and material possible, nano fluid require special disposal	(-) Complex system, many intricate parts (–) Difficult maintenance within coolant loop, multiple sensors for pressure regulation necessary, frequent refill of reservoir (-) Damage to system for off-design operation, (o) Many systems to dispose, recycling of parts and material for most subsystems possible	(-) Intricate and expensive integration into stack design, simple overall system (-) Exchanging of wick or injectors complicated and expensive, disassembly of stack necessary (-) Wick degrading over time, limiting long term water transoprt (+) Few components, disposal unproblematic
				(+)	(+)	**(o)**	(+)	(+ +)	**(o)**	(-)	(-)	(-)
				(+ +)	(+)	(+)	(+)	(+ +)	(-)	(-)	(–)	**(o)**
			Result	**5**	**4**	**4**	**4**	**5**	**2**	**2**	**1**	**3**

Table 9 Technology readiness and development (T) Evaluation Overview; (–) corresponds to very bad fulfillment, (-) bad, (o) neutral, (+) good, (++) very good

Criteria		Criteria definitions	Conductive Cooling			Air Cooling		Liquid Cooling		Phase change cooling	
			Passive	Conductive material (Edge flow)	Heat pipes (Edge flow)	Designated channel	Cathode flow	Water, Oil, Glycol	Nano fluids	Boiling loop	Cathode Evaporation
Technology readiness and development (T)	(w = 0.1)	Technology readiness level (4) Research gap (3) Possible breakthroughs & Disruption potential (5)	(+) Systems tested in operating environment "**6**" [80]-[Moussa.2023] (–) No clear next step (–) No foreseeable breakthroughs, technology not feasible for use in aviation drive train	(-) Some laboratory investigations using air as well as water edge flow "**4**" [28]-[Wen.2011] (o) Demonstrations for larger stacks needed, integration of heat spreaders into BPP (+) Highly conductive unisotropic materials, composite heat spreaders and the integration of conductors into the BPP might enable the use in larger stacks	(o) Multiple laboratory investigations under different boundry conditions "**5**" [31]-[Supra.2014] (o) Investigations of scalability, further demonstrations of edge flow effectiveness needed (++) Possibility of integration into BPP for weight and volume reduction, investigations of pulsating heat pipes in fuel cell presents opportunity for performance enhancement	(+) Multiple laboratory investigations under varying boundary conditions "**5**" [47,51]-[Dsouza.2020,Reddy.20] (++) Technology well understood (-) No foreseeable breakthroughs	(+) System prototypes of portable stacks operational "**7**" [44]-[Heras.2020] (+) Technology well understood, reduction of parasitic power presents central challenge (-) No foreseeable breakthroughs	(++) Industry standard, especially for LT-PEM, less established for HT-PEM "**8**" [81]-[Power Cell Group-Aviation application] (++) Technology well understood (-) No foreseeable breakthroughs	(-) Analytical and numerical investigations have shown potential, technical implementation in HT-PEM FCs is still pending "**3**" [63]-[Islam.2016] (–) Many open questions and challenges need to be overcome to demonstrate feasibility (+) Possibility to improve heat transfer, minimize parasitic power and system weight	(–) Conceptual studies, further research and implementation pending "**2**" [82]-[Guan.2020] (–) A lot of research required to advance system concept (++) Possibility to drastically increase specific heat rejection of the TMS, while also reducing parasitic power	(-) Some laboratory investigations using wick, theoretical studies employing injection "**3**" [76]-[Hwang.2016] (-) Research into application for HT-PEM FCs needed (o) Application for HT-PEM could prove to be advantageous for this cooling architecture
			(–)	**(o)**	(+)	**(o)**	**(o)**	(+)	**(o)**	**(o)**	**(-)**
		Result	**1**	**3**	**4**	**3**	**3**	**4**	**3**	**3**	**2**

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Declarations

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