INNOVATIVE THERMAL MANAGEMENT SYSTEMS FOR FUEL CELL ELECTRIC AIRCRAFT

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INNOVATIVE THERMAL MANAGEMENT SYSTEMS FOR FUEL CELL ELECTRIC AIRCRAFT

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ABSTRACT

The Thermal Management System (TMS) is a crucial component of the aircraft, particularly in case of layout exploiting a high level of electrification of propulsion systems. Specifically, use of fuel cells in aviation industry appears to be extremely challenging, due to the significant amount of waste heat produced. Therefore, the aim of this paper is introducing some technical solutions proposed by the literature for an effective thermal management of the aircraft. Particularly, the identification of most relevant heat sinks for the aviation is performed, with a specific interest for solutions exploiting the stored fuel intrinsic heat capacity. The example of a conceptual hybrid-electric, fuel cell powered, turbo-propeller driven, regional transport aircraft is then described. The Model Based System Engineering (MBSE) methodology is applied to define the system use cases and to identify the most relevant requirements. A possible system architecture is finally proposed. The paper provides some considerations over the topic of fuel-based TMS (F-TMS) to the specific case of hybrid-electric, fuel cell, regional aircraft.

Keywords: Fuel cell, Thermal management, Hybrid-electric, Aircraft, Tank

1 INTRODUCTION

During the last fifty years, the topics of environmental preservation, sustainability and pollutant emissions reduction became increasingly relevant factors in the design of all engineering products and processes [1]. Current relevance of such themes is evidenced by numerous international agreements, declarations, acts and even regulations, such as the UN Agenda 2030 of "Sustainable development goals" [2], or the European Strategic Research and Innovation Agenda (SRIA) targets for EU aviation by 2050 (Flightpath 2050) [3]. Furthermore, creation of specifically purposed joint undertakings, such as Clean Aviation [4], previously Clean Sky, undeniably proves the relevance and consistency of such themes. Amongst the various targets of the clean aviation joint undertaking, carbon neutrality and net green-house emission reduction of no less than 90% when compared to the 2020 state of the art for regional transport aviation are just some of the main objectives of this venture, while nullification of pollutants emission as well as engine noise during ground based operations are also desirable.

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1.1 CONTEXT AND DRIVERS

During this extended time-frame, in fact, several national and international funding programs, as well as sanctions for those companies not capable of meeting the expected environmental goals, placed the theme of sustainability progressively closer to the focus of industrial research, especially in the case of the transport sector. Electrification of propulsion systems, clearly arose as a most prominent solution for the creation of low environmental impact machines and vehicles. Amongst these, the automotive sector represents, arguably, the main driver of off-he-grid transport electrification. Plenty of studies, demonstrators, and even commercial products can be found implementing full, or at least partial, propulsion electrification via mounted electric energy storage devices in the automotive, as per the review of Rani and Jayapragash [5]. In particular,

Table I - Adopted acronyms and abbreviations.

Acronym	Meaning
BDD	Block Definition Diagram
EASA	European Aviation Safety Agency
ECS	Environmental Control System
FADEC	Full Authority Digital Engine Control
F-TMS	Fuel-based Thermal Management System
HE	Heat Exchanger
HT-PEM	High Temperature-PEM
HS	Heat Sink
IBD	Internal Block Diagram
INCOSE	INterantional COuncil of System Engineering
LT-PEM	Low Temperature-PEM
MBSE	Model-Based Systems Engineering
MT-PEM	Medium Temperature-PEM
PAX	Passengers number
PEM	Proton-exchange membrane (fuel cell)
RFLP	Requirements, Functional, Logical, Physical
ROM	Reduced Order Model
Tit.-Abs.-Key	Title-Abstract-Keywords
TLR	Technology Readiness Level
TMS	Thermal Management System

Table II - Adopted variables.

Variable	Description
$m_f(t)$	Fuel mass stored in a generic tank
$m_{f,Mtank}(t)$	Fuel mass stored in main tank
$m_{f,Rtank}(t)$	Fuel mass stored in recirculation tank
$\dot{m}_{f,brn}$	Fuel mass flow burnt by the engines
$\dot{m}_{f,rec}$	Fuel mass flow recirculated to tank
m_{HE}	Heat exchanger mass
$\dot{m}_{pump_{cool}}$	Coolant mass flow at the pump
$\dot{Q}_{HE-FC}$	Heat flow absorbed from fuel cell
$\dot{Q}_{out}$	Heat flow rejected via auxiliary ram-air cooler
$\dot{Q}_{rejected}$	Heat flow rejected through tank walls
$\dot{Q}_{waste}$	Waste heat flow
T_{cold}	Inlet temperature of cooling air
$T_f(t)$	Fuel temperature of a generic tank
T_{FC}	Fuel cell temperature
$T_{FC_{lim}}$	Fuel cell limit temperature
$T_{f,Mtank}(t)$	Fuel temperature of main tank
$T_{f,Rtank}(t)$	Fuel temperature of recirculation tank
$T_{HE_{cool,in}}$	HE inlet coolant temperature
$T_{HE_{cool,out}}$	HE outlet coolant temperature
$T_{HE_{fuel,in}}$	HE inlet fuel temperature
$T_{HE_{fuel,out}}$	HE outlet fuel temperature
T_{lim}	Limit temperature of a generic heat source
$T_{lim,HT}$	Limit temperature of a high temperature heat source
$T_{lim,LT}$	Limit temperature of a low temperature heat source
$\dot{T}_{pump_{cool,out}}$	coolant temperature at pump outlet
α	Recirculated fuel mass flow to total fuel mass flow ratio

opportunities offered by the combination of conventional and electric propulsion devices had been thorough investigated, as per the works of Castellano and Cammalleri [6], and Spano et al. [7], on hybrid-electric solutions design and optimization.
On the other hand, air-based transport was not involved in major electrification programs just until the last few decades. In fact, the introduction of significant amounts of electric devices, up to the complete electrification of the propulsion system, had always been hindered by the stringent weight and safety requirements intrinsic with the sector [8, 9]. Specifically, one of the most challenging detriments to this technological leap consists in the disadvantageous energy-to-weight ratio provided by currently available electric energy storage devices, when compared to conventional jet-fuels' specific energy of about 12 kWh/kg [10]. As of current state of the art technology, the two main representatives of such devices are the Li-ion batteries, with a specific energy of about 0.25 kWh/kg [11, 12], and the hydrogen-powered Proton-Exchange Membrane (PEM) fuel cells, with a total system energy-to-weight ratio ranging from 0.6 to 1.2 kWh/kg [13]. The difference between these values and the specific energy of conventional jet-fuel is so prominent that the resulting increase in the aircraft total mass often forces the whole system to be oversized up to the point of nullifying any environmental benefit provided by the electrification process in the first place. Indeed, some experts forecast that the suitability of electric energy storage devices for medium-to-big scale aircraft applications will not be achieved before 2050 [14, 10], assuming that current trends in average battery capacity growth are not changed, and that a specific energy of about 1.5 kWh/kg is achieved.
These considerations render the development of hybrid-electric aircraft preferable over the commitment into full electric conversions, at least in the short term. Such a compromise is vital for near future electrification since it allows to benefit from the reduced environmental impact provided by the electric powertrain while still relying on the consistency offered by conventional combustion engines. Moreover, the introduction of hydrogen-powered fuel cells in place of electro-chemical batteries appears as a more feasible solution for next-gen aircraft electrification [8], consequent

to their favourable energy-to-weight ratios, when compared to conventional lithium batteries. However, careful design and optimization of the integrated hydrogen storage devices, fuel cell stacks, and supply pipes is crucial for such an advantage to be harnessed, as evidenced in the work of Maraschi et al. [10], and Cinar et al [15]. Hence, efforts towards environmental impact reduction in near future aviation programs can reasonably be expected to likely rely on one or both of the following concepts: hybrid-electric powertrains, and hydrogen-fuel cell energy storage.

1.2 FUEL CELLS & HYDROGEN

The main advantage provided by fuel cell technology to the aerospace sector relies in the extremely high gravimetric energy density offered by hydrogen as an energy vector, possessing an outstanding net specific energy of about 33.3 kWh/kg [16], almost three time the value of typical kerosene-based jet-fuels. Conversely, however, hydrogen presents a rather poor volumetric energy density when compared to conventional fuels, requiring either to be stored at cryogenic temperatures, or under extremely high pressures of up to 700 bar. The resulting net energy-to-volume ratio of hydrogen is thus of about 3 kWh/l [16], compared to the 10 kWh/l of kerosene.

Furthermore, complex materials and designs have to be employed for the tanks, as to limit the boil-off phenomenon of liquid hydrogen [17], and the permeation of compressed hydrogen [18], leading to progressive loss of the gas through the tank walls. This results in the need for encumbering hydrogen tanks and distribution systems to be installed on-board, inevitably reducing passengers and payload capacity of a given aircraft, as well as augmenting the overall weight. Consequently, when the whole hydrogen-fuel cell system is considered, accounting for the masses of the tanks storing the hydrogen and the fuel cells converting it into electric power, a real energy-to-weight ratio of roughly 1 kWh/kg is obtained, as anticipated. However, despite these challenges, hydrogen arguably remains a preferable energy vector over batteries for the electrification of the aircraft sector, as testified by several studies from the industries [19, 20] and academia [21, 22, 23, 24] addressing more-electric aircraft development and fuel cell technology investigation. A number of demonstrators can also be found in the general aviation sector, such as the Boeing Fuel Cell Demonstrator from 2008 [25], the NASA X-57 (in its early iterations) [20], and the HY4 commercial aircraft from the H2FLY company (DLR) [26]. Commitment of the industry towards the development of larger electrified aircraft employing hydrogen-fuel cell technology is also testified by several initiatives, including the ZEROe program from Airbus [27], or the many projects from ZeroAvia [28], including the first test flight of a retrofitted Do228, small regional transport aircraft and commuter [29].

Concerning the actual fuel cells, a number of different technologies currently exist in the literature [30] supporting hydrogen conversion into electrical power. Amongst these, the Proton-Exchange Membrane fuel cells are arguably the most widespread solutions and the most frequent in the transport sector. These are further differentiated into high temperature PEM fuel cells (HT-PEM), with an operating temperature of 120 to 200 °C, and low temperature PEM fuel cells (LT-PEM), typically operating around 60 to 80 °C [30]. Between these two, the LT-PEM appear to be the favoured solutions thanks to a faster startup, higher power density, and enhanced robustness. However, despite PEMs' advantages over Li-ion batteries in terms of overall system weight, fuel cells are hindered by a much lower efficiency of the stacks compared to batteries, whose efficiencies exceed 90% [31]. PEM fuel cells, on the other hand, struggle to exceed efficiencies of about 50% under operative conditions [30, 32]. This is a crucial aspect since, for each kW of electric power being generated inside the cells, a roughly equivalent amount of waste heat gets produced as well. This phenomenon forces the need for the introduction of a system capable of effectively absorbing said waste heat, transporting it away from the source, and dissipating it into an purposefully chosen heat sink, in order to prevent the uncontrolled heating, and subsequent damage, of the fuel cell stacks. A process that is made even more difficult by the relatively low temperatures limits of about 70 to 80 °C, required by LT-PEMs. Innovations in the field of PEM membrane materials aim to ease these issues through the development of new, medium temperature, PEM fuel cells (MT-PEM), capable of operating between 100 and 120 °C with minimal damage to the membranes [33, 34, 35]. However, challenges remain.

In fact, management of such low grade high amount waste heat still represents a major challenge, with the topic of adequate fuel cell cooling being examined in many studies, as summarized in the work of Bargal et al. [36]. These challenges appear to be even more prominent in the prospect of aerospace applications, consequent to the very high powers involved with aircraft propulsion, often exceeding several MW, and the high cruising speeds of aeroplanes, causing any induced drag from the radiators to significantly hinder the aerodynamic performance. Traditional aircraft heat sources such as electronics [37], the Environmental Control System (ECS) [38], and other on-board devices, are not subject to such challenging constraints as they are typically associated with lower heat loads, rarely exceeding 50 to 100 kW of combined waste heat generation. Turbines, on the other hand, involve both very high waste heat generation and high operating temperatures, but these are almost entirely rejected into the atmosphere through the exhaust gases. This reduces the need for heat dissipation units and a coolant circuits, as the main challenge with turbines becomes the adequate screening of blades and components from extreme heat via the formation of a small air film surrounding the surfaces [39].

Finally, as the fuel cell is an electric device, care should be taken when designing the TMS as to prevent electric discharges and short circuits from propagating through the cooling circuit. Adequate dielectric coolants, based on ethylene glycol-water mixtures, shall thus be employed, along with the introduction of a deionization filter in the coolant loop [40].

1.3 THERMAL MANAGEMENT SYSTEMS

Consequently, the effective design of the Thermal Management System (TMS) is to be considered a crucial asset in any expected hydrogen fuel cell application in the aviation industry. Therefore, this paper aims at investigating, analysing, and describing several TMS solutions specifically suited for the development of hybrid-electric aircraft exploiting hydrogen-based energy storage and fuel cells energy conversion units. In the following are thus presented, first and foremost, all the most relevant solutions currently available in the scientific literature for thermal management in the aeronautical field. In an effort to conceptualize the TMS at system level, with a specific focus towards the integration of its various components, a classification and confront between relevant available heat sinks is performed. Amongst the proposed architectures, a deepening of fuel tank-heat sink solutions is specifically carried out, with the intention to fully exploit the benefits provided by the presence of conventional jet-fuel in hybrid propulsion aircraft. Finally, MBSE methodologies are applied to guide the definition of a possible design, through the use of the ”V-model” diagram and the RFLP analysis, leading to a preliminary requirements analysis of the fuel-based TMS, and a possible architecture proposal, in the prospect of future numerical simulations.

2 LITERATURE SURVEY

In an effort to propose an effective tool to provide fuel cell waste heat disposal in aircraft application, an extensive analysis of current state of art of TMS solutions was carried out. A wide selection of scientific publications was identified by means of bibliographic research, providing an array of different cooling options and associated architectures. In particular, the works of Van Heerden et Al. [41], as well as Coutinho and others [42, 43, 44, 45, 46], present a brief, yet complete description of all the most relevant cooling solutions currently applied, designed or theorized in the aviation field. Subsequently, the research is specialized towards the topic of heat disposal, since the identification of a suitable heat sink for the dissipation of fuel cells, relatively low grade, high heat fluxes is a most challenging aspect. Amongst the various options, exploitation of intrinsic heat capacity of, tank stored, conventional jet-fuel is further analysed, in the prospect of usage onboard of hybrid-electric aircraft combining fuel cell powered electric propulsion and traditional turbomachinery.

2.1 METHODOLOGY

The bibliographic research is pursued with the aid of Scopus online publication database. Coherently with previous statements, the collection of relevant articles on the topic of fuel-based thermal management systems is realized through the adoption of the keywords and search criteria presented in table III.

Table III - Scopus research string criteria.

Criteria	Specification
Tit.-Abs.-Key	”thermal management” OR ”temperature control” OR ”cool*”
Tit.-Abs.-Key	”aircraft” OR ”airplane” OR ”aeroplane” OR ”airborne” OR ”aviation” OR (”aerospace” AND NOT ”spacecraft”)
Tit.-Abs.-Key	”heat sink” OR ”heat absorb*” OR ”heat exchang*” OR ”heat reject*”
Tit.-Abs.-Key	”fuel” OR ”tank”
Subject area	Engineering
Language	English
Database	Scopus

2.2 SURVEY RESULTS

The adoption of the previously described research string provides a total of 423 results specifically focused towards the use of fuel tank as an aircraft relevant heat sink. Documents are spread over a relevant time span: from the first investigations on the subject fuel-based TMS during the 60s race for increasingly faster super-sonic aircraft to the 80s and 90s challenges associated with the introduction of high power electronics in high-performance aeroplanes, till the most recent efforts towards aircraft electrification programs.
Overall, the results of this research can be considered very promising for a number of reasons. Firstly, the ample selection of documents identified supports the feasibility of fuel-based thermal management systems, at the very least, from a conceptual standpoint. Second, a significant increase in the number of yearly publications over the course of the last ten to fifteen years, demonstrates the growing interest of the scientific community towards the topic of innovative TMS, as shown in Fig. 1.
Another interesting aspect to evaluate by analysing the explored collection of documents, is the presence of a percentage of conference papers (63%) doubling that of the published articles (32%). This significant difference in the document type distribution may suggest that the topic of fuel-based TMS is still matter of debate in the scientific community, still offering potential for further development over this subject. In fact, many of the proposed papers discuss the possibility to introduce such cooling tools for the management of the ever increasing thermal loads associated with the growing power of aircraft avionics and

Table IV - Collection of most relevant documents on the topic of fuel-based thermal management systems, classified on their context, application, focus and solution.

Context of the research and purpose of TMS	References
Cooling in support of propulsion electrification via non-specific, or different, energy storage devices	[47], [48], [49] [50]
Cooling in support of hybrid propulsion electrification via turbo-electric architectures	[51], [52]
Cooling in support of hybrid propulsion electrification via electric batteries	[53], [54], [55], [56], [57]
Cooling in support of full propulsion electrification via hydrogen fuel cells	[58], [59], [60], [61], [62]
Medium sized aviation and regional transports (up to 150 PAX)	[63], [64]
Numerical modeling and design	[65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [66], [63], [64], [76], [77]
Confront between different architectures and system optimization	[57], [78], [79], [80], [81], [82], [83]
TMS integration into the whole aircraft assembly	[84], [48], [55], [56], [85]
Single tank architectures without fuel recirculation, HE on the feed-line	[51], [77], [86], [87], [88]
Single tank architectures with fuel recirculation	[73], [74], [84], [65], [56], [57], [89], [79], [52], [64], [67], [68], [85], [90], [71], [91], [92], [93], [94]
Dual tank architectures with fuel recirculation	[95], [78], [76], [80], [81], [82]
Tank array architectures with fuel recirculation	[96], [48], [70], [97], [72]

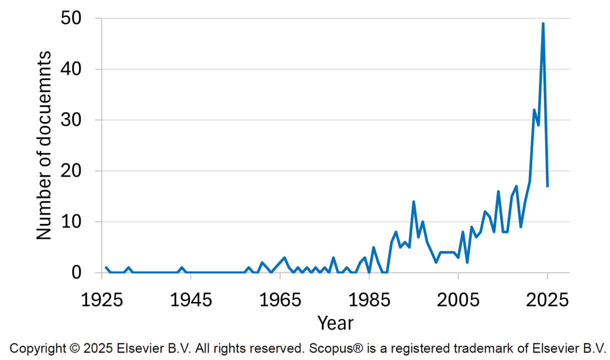

Figure 1 Number of publications per year on the topic of aviation-based, fuel tank-heat sink TMS, provided by Scopus database as of Apr 2025.

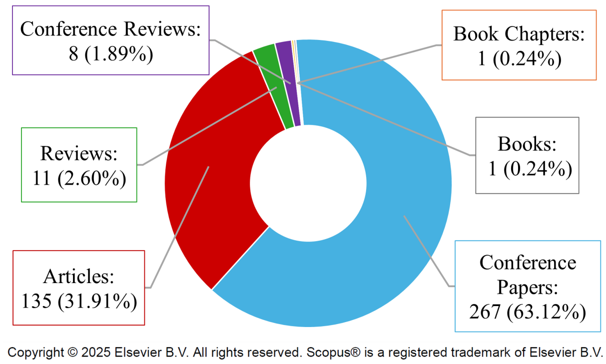

Figure 2 Publication types, and relative distribution, on the topic of aviation-based, fuel tank-heat sink TMS, provided by Scopus database as of Mar 2025.

other electronic devices. On the other hand, focus on the possibility to exploit passive heat rejection through the tank surfaces is also discussed in some papers. Finally, the presence of a number of reviews describing the use and concepts of fuel-based TMS is also a relevant factor, indicating that such a topic is already well established in the literature and, therefore, that its viability is proven. Fig. 2 shows all of the previously stated concepts.

For an easier selection and clusterization of found documents concerning the topic of fuel tank-heat sink TMS, the most relevant papers are collected and classified in Tab. IV. Articles, and conference papers are there subdivided and characterized on the basis of their intended use case, the adopted methodology and the overall focus of the research, as well as the architecture of the fuel tank assembly.

3 THERMAL MANAGEMENT SOLUTIONS FOR AVIATION

The collection of examined articles and, especially, reviews allows us to determine the presence of a number of different designs and architectures suitable for the purpose of effectively managing produced waste heat. These solutions

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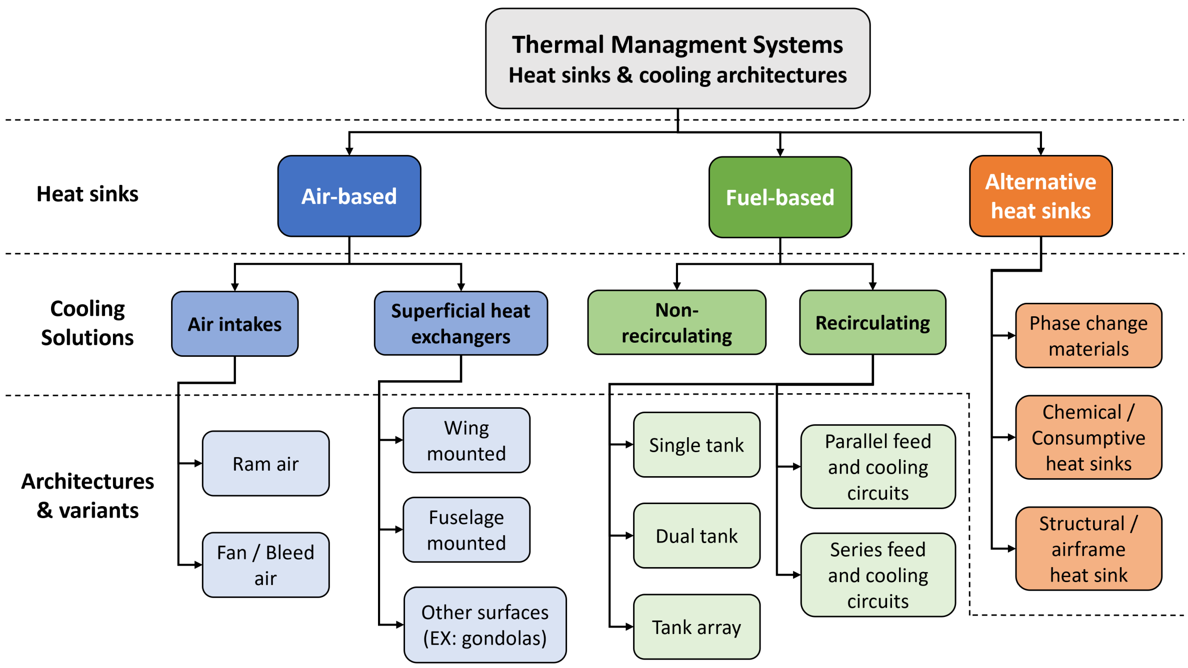

Figure 3 Classification of main thermal management systems in the aviation field, based on the adopted heat sinks.

are numerous and require a classification. There are many aspects that may be taken into account while defining the various TMS, however, one of the most relevant is the intended main heat sink of the system and, therefore, the proposed classification will be centered around this topic. For clarity's sake, we intend as a main heat sink of the TMS, the element, or component, where the waste heat produced by the heat source, a fuel cell in this case, will ultimately be transferred and collected. The adopted classification is driven by the work of Petkus and Gallington [98] and, especially, by the reviews of Van Heerden et al. [41], and Coutinho and et al. [42]. In the end, three main heat sinks could be identified: air, fuel or alternative heat sinks, which may be further specified into their own sub-categories, as shown in Fig. 3. Said specifications could relate to either: different design shapes, such as ram and superficial air cooling; opposing circuital architectures, such as recirculating and non-recirculating fuel flows; or even alternative cooling processes, such as phase change material state transitions and chemical heat sinks molecular reactions. However, it is also worth noting that, in the end, air is usually the actual final heat sink of the aircraft, since the heat absorbed by fuel is later ejected into the atmosphere via the engine fumes, while other kinds of heat sinks are also subject to heat cession to the ambient, one way or another.
In the end, all of these solutions come with a number of advantages, limitations, preferable use cases, and Technology Readiness Levels (TRL), which are here briefly summarized.

3.0.1 Air-based solutions

Air-based solutions represent the most common devices in thermal management, since the exploitation of surrounding air provides simple, yet effective, cooling, without introducing any inherent threats to the overall aircraft safety. Furthermore, since the external environment effectively acts as an ideal heat sink, not modifying its average temperature despite exchanging heat with the aircraft, air-based solutions also benefit from an unlimited heat capacity throughout the mission. On the other hand, since the heat sink is located outside of the aircraft, the overall cooling effectiveness of the system is also significantly influenced by external factors, such as the eventual presence "hot day" conditions or variations in flight altitude.
The main devices and designs employing air as an heat sink are:

1. The ram-air. These solutions supply air to internally mounted heat exchangers via purposefully shaped inlets on the aircraft surface. Ram-air designs are very common in the industry, as they provide simple and effective cooling. However, a drag penalty is also introduced by the ram structure, which hinders aircraft aerodynamics. Furthermore, ram air cannot provide cooling when the aircraft is stationary, unless a fan is mounted on the outlet duct.
2. The Bleed-air. These solutions extract a portion of the airflow compressed by the engines to employ it for cooling and cabin pressurization. The airflow is granted as long as the engines are kept spinning,

allowing cooling even when the aircraft is standing still. Nonetheless, compressor bleed-air is subject to significant heating, making it suitable only to cool high temperature components, like the turbine blades. However, in case the adopted propulsion system employs some kind of ducted fan architecture, fan bleed-air can also be extracted. Fan-air is generally subject to much smaller compression heating, making it suitable for cooling more sensible components. Bleed air preserves overall aircraft aerodynamics, but excessive bleed can significantly decrease engine performance, resulting in increases fuel consumption.
3. The superficial heat exchangers. These solutions dissipate waste heat directly into the atmosphere through the aircraft's fuselage and wings, preserving the aerodynamic performance of the aeroplane. Superficial heat exchangers offer effective cooling when the aircraft is traveling at high speeds, however, this system is made almost completely useless when stationary. Moreover, careful design is needed to prevent the heat transfer from developing flow separation on wings, the intrinsically high mass of such a distributed system needs to be addressed thoughtfully. These issues caused the superficial heat exchanger design to be employed only in some very niche applications.

In the end, ram-air designs appear as the most promising air-based solutions for fuel cells cooling, as long as the powers involved are maintained relatively low. Higher degrees of electrification are in fact expected to result in increasingly higher system induced drag. Bleed solutions do not appear to be suitable for fuel cells cooling, unless some kind of ducted fans are employed in the propulsion units. Finally, superficial heat exchangers show promise in supporting fuel cell cooling while preserving aerodynamic performance. However, tradeoffs with respect to total system mass should be evaluated carefully, while significant limitations in stationary cooling call for the integration of this solution with other systems.

3.0.2 Fuel-based solutions.

Fuel-based solutions are the second most common devices in the industry. They exploit the intrinsic heat capacity associated with the masses of fuel being stored inside tanks, leveraging on a resource that is already being hauled by the aircraft. Fuel is also an advantageous vessel for heat transport when compared to air, thanks to it being liquid and presenting favourable heat transfer coefficients. This results in lower mass flows being required and more compact heat exchangers being employed. Moreover, since the fuel is stored inside the aircraft, greater control is achieved over the heat sink, decoupling cooling from external factors such as aircraft speed, hot day conditions, and altitude.

On the other hand, flammability and potential explosive hazards are of primary concern in fuel-based TMS, requiring continuous and precise monitoring of fuel temperature and evaporation as well as the introduction of a fuel tank inerting system [99]. The total stored fuel mass is, in fact, limited by the available tank volume and mission flight requirements, causing the final heat capacity of the heat sink to also be limited. This prevents fuel from behaving like an ideal thermostat, causing its temperature to progressively rise throughout the flight. Consequently, a fuel-based TMS is capable of providing effective cooling only until the fuel temperature reaches a given threshold, which is either set by safety regulations or by the heat source's temperature limit. Reaching this threshold defines the overall system's "thermal endurance", which contributes to determine the the maximum achievable range of the aircraft.

A number of different F-TMS architectures exists, yet they will be discussed in greater detail in Sect. 3.1.

In the end, fuel-based Thermal Management Systems appear as promising solution for fuel cells cooling, as they preserve the aerodynamic performance of the aircraft and, for the most part, allow effective cooling independently of external conditions. They could be used in place, or to support, conventional ram-air cooling, especially when in stationary conditions. They are also advantaged by the fact that they are not not subject to compression heating prior entering the heat exchanger. However, the use of F-TMS for fuel cell cooling is strictly limited to the context of hybrid-propulsion electrification and clearly not suitable for full electric aircraft. Furthermore, the effectiveness and performance of fuel-based solution is progressively diminished at higher degrees of hybridization, consequent to the stored fuel mass being smaller.

3.0.3 Alternative heat sink solutions

With the term alternative heat sink solutions, we refer to all those devices employed, designed, or conceptualized, that do not directly rely on fuel, or air, to assist in the thermal management of an aircraft. These are the least common designs, are often associated with a low TRL, and are almost always combined with other, more conventional, cooling architectures. In fact, alternative heat sinks are often used to absorb peak heat loads, such as during takeoff, and later dissipate the stored heat over an extended time-span, allowing for the downsizing of other, more conventional, TMS elements. Nonetheless, alternative heat sinks can also be employed as main heat sinks for some specific low endurance use cases.

The main categories of alternative heat sinks are:

1. The phase change materials. These devices leverage on physical state transition of a material, typically fusion, to absorb heat from a heat source. Phase change materials, unlike fuel, provide the added benefit of acting as an actual thermostat. However, weight of such components can quickly become prohibitive, while the the actual materials could either be: costly, toxic or subject to cyclic degradation.

2. The chemical heat sinks. These devices absorb heat via endothermic chemical reactions, and are typically installed in modules. However, since the reactions involved in chemical heat sinks are often irreversible, such modules tend to come as consumable packages, and are not suited for long endurance cooling.
3. The structural heat sinks. These solutions simply represent the collection of all elements places in proximity of the heat source, that are capable of absorbing and storing heat from it though conduction. However, the heat capacity of structural heat sinks is often limited, making them only suitable for minimal heat loads management.

Overall, alternative heat sinks do not appear as indicated solutions for fuel cell cooling, either due to limited cooling capacity or significant added weight. Amongst them, phase change materials could arguably offer some advantages in reducing cooling requirements while considering fuel cell peak load generation, such as during take off.

In the end, looking at the results of this survey, conventional ram-air and fuel-based solutions appear as the two most promising solutions to provide fuel cell cooling in support of hybrid-electric aircraft development. Amongst these, air-based designs have already been thoroughly explored in the literature, evidencing challenges in the management of system induced drag. On the other hands, harnessing of the benefits offered by fuel-based architectures in support of fuel cell cooling still needs to be addressed. Therefore, as anticipated, this theme is further analysed in the following.

3.1 FUEL-BASED THERMAL MANAGEMENT SYSTEMS

The documents obtained via the literature analysis, described in Sect. 2 present an ample collection of theorized, conceptual, modeled, tested and applied fuel-based cooling architectures. The proposed solutions vary on a number of aspects, from the detailed numerical modeling of the tanks internal behaviour via CFD analysis to a more generic system level design of the architectures. The former allows to distinguish between two major types of fuel based solutions. The main, or terminal, fuel heat sink tend to conceive the fuel as their prevalent or unique heat sink. Heat is expected to be absorbed by the fuel, without major portion of it being transferred to the external ambient. Hence, the collection of tanks can often be assumed as an adiabatic system with respect to the environment. Such an hypothesis is very well suited for modeling of applications whose thermal conductivity to the external atmosphere is hampered by the materials adopted to build the tanks or the frame like, for example, composites and polymers.

The secondary or temporary fuel heat sink, on the other hand, do not conceive fuel as their prevalent heat sink but, rather, as complementary element. Fuel is meant to absorb heat from the heat source, only to cede it at a later stage to some other heat sink, most likely, the external environment. Two main approaches are proposed in this sense. The work of Kellermann et al. [57] for example, presents several configurations where the fuel acts as a sort of coolant for the heat source, whose purpose is to cede heat to the external ambient through the tank walls. Some of the proposed solutions even try to further enhance the process via the integration of superficial heat exchangers surrounding the tanks themselves. On the other hand, the "Hot/Cold Tank Recirculation with Tank Drains" design proposed by Doman [82], describes the possibility to exploit fuel as a secondary heat sink by having a small tank subsystem partitioned into two separated cold and hot tanks, with the later containing the exploited fuel to either be burnt in the engines or slowly cooled back to the original temperature via alternative means, such as ram air. Such a solution focuses on the possibility to use fuel as a thermal buffer in case of discontinuous, peak heat loads, with the intent of progressively ceding the majority of said heat to other heat sinks, at a later stage. For the purpose of this paper, a collection of different architectures is here presented, all suited for use both as main or temporary heat sinks, despite the latter being only truly relevant in designs allowing for fuel recirculation. In the end, about five main architectures could be identified according to: the presence or absence of a recirculation circuit, the placement of the main heat exchanger, and the compartmentation of the various tanks, as represented and discussed in the following.

3.1.1 Fuel-based TMS with submerged heat exchanger

Fuel-based TMS with submerged heat exchanger, represented in Fig. 4, are amongst the simplest possible F-TMS architectures, realized by placing the main heat exchanger directly inside the fuel tanks. Heat transfer from the heat exchanger to the heat sink occurs via natural convection, while progressive temperature increase in the tanks allows for design centered around secondary heat sink and passive heat exchanger concepts.

Overall, the main advantages of such an architecture are:

- The intrinsically reduced need for additional drag-inducing air-intakes;
- The simplicity of the design;
- The direct contact between the heat sink and the heat exchanger, reducing the need for pipings and saving weight;
- The possibility for the tank to effectively act as passive heat exchanger via progressive temperature increase in tank.

Nevertheless, the following hindrances could also be identified:

- The natural convection heat transfer mechanism is less effective when compared to forced convection, thus limiting the maximum manageable heat flow, or forcing the heat exchanger oversizing;

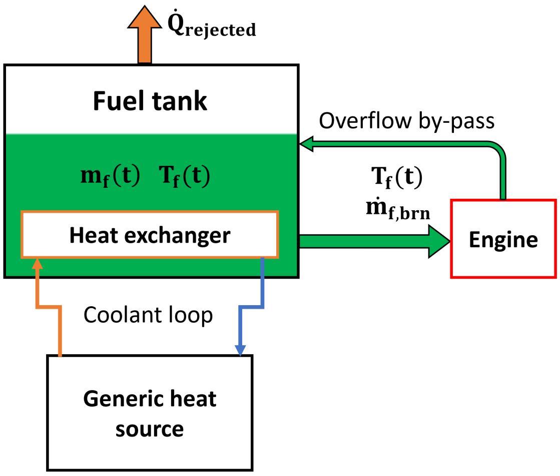

Figure 4 Fuel-based TMS with submerged heat exchanger.

- The natural convection phenomenon is not directly controllable, posing some issues in the management of high and discontinuous loads;
- The progressive temperature increase and fuel evaporation inside the tanks represent a relevant flammability hazard to be monitored and managed.

Consequently, F-TMS with submerged HE represent ideal candidates for component cooling of systems placed in proximity of aircraft fuel tanks, that are also characterized by limited heat flux production, such as the actuators or the lubrication circuit [100]. Nevertheless, the possibility to further develop the architecture for the effective management of higher heat fluxes is also proposed in some studies [57].

3.1.2 F-TMS with heat exchangers on the feed-line

F-TMS with feed-line heat exchangers, represented in Fig. 5, have the heat exchanger being placed along the supply-line to the engines, rather than inside the fuel tanks. This allows for development of forced convection heat exchange inside the heat exchanger which is beneficial for the overall efficiency of the system and the maximum achievable heat transfer. No excess of fuel mass flows is expected to be directed back to the tanks, since eventual overflows are simply bypassed directly to the entrance to the pump. For this reason, this kind of architecture is the only one that is entirely non-feasible for usage of fuel tanks as passive heat exchangers, since the temperature increase cannot occur.

Overall, the main advantages of such an architecture are:

- The reduced need for additional drag-inducing air-intakes;
- The simplicity of the design;
- The maximization of fuel heating prior injection into the combustion chamber of the engines is beneficial to the overall combustion efficiency of the aircraft, according to several studies;
- The direct consumption of heated fuel prevents fuel temperature increase inside the tanks, thus significantly reducying the safety hazard associated with the system.

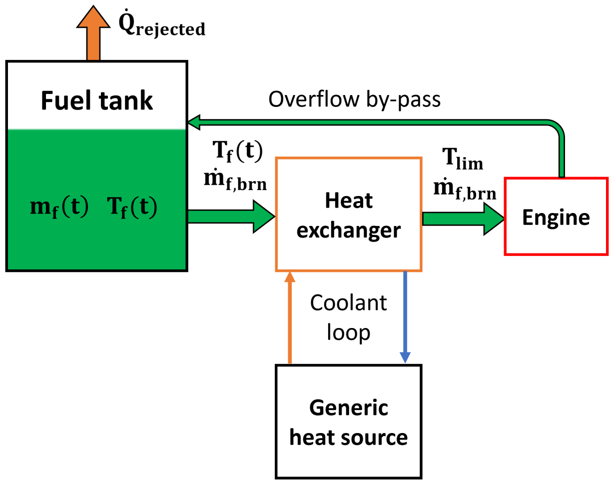

Figure 5 Fuel-based TMS with feed-line heat exchangers.

Nevertheless, the absence of a recirculation pipeline comports the impossibility to increase the fuel flow passing through the heat exchanger beyond the instantaneous needs of the engines. Therefore, the following hindrances could also be identified:

- The maximum realizable mass flows, and consequently the maximum realizable heat flux absorbtion are limited to the maximum achievable fuel flow request by the engines;
- The instantaneous fuel flow passing through the heat exchanger does not depend from the evolving needs of the heat source, yet rather from the fuel consumption curve of the mission profile. Therefore, no direct control over the cooling fuel flow is achievable, rendering mandatory the adoption of auxiliary cooling units, such as ram-air intakes for the management of excessive heat load phases;
- The impossibility to heat the fuel inside the tanks, prevents the use of the fuel-TMS as a passive heat sink.

As a consequence, this architecture is really suited for use as a simple and safe cooling system to be adopted in low heat load applications, preferably close the the engine compartment. Therefore, in fact, fuel-based TMS with feed-line heat exchangers are already very common in the industry, and frequently find application in gearbox lubricant oil cooling for turbofans driven airliners.

3.1.3 F-TMS with heat exchanger in parallel recirculation

F-TMS with heat exchanger in parallel recirculation, represented in Fig. 6, introduce the possibility to return excess fuel back to the tank via a dedicated pipeline. The heat exchanger placement does not occur along the pipeline leading to the engines yet, rather, on dedicated circuit separately located and pumped. From here the name

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”recirculating-parallel”, and the possibility to completely decouple the thermal circuit from the feed one. This aspect renders such an architecture particularly favourable for eventual retrofitting of already existent fuel tank arrays into integrated F-TMS. Overall, the main advantages of such an architecture are:

- The reduced need for additional drag-inducing air-intakes;
- The relative simplicity of the design, albeit the number of pumps, sensor and controls is higher than in the previous cases;
- The suitability for easy retrofit of already existent fuel tank systems.
- The parallel circuit allows to decouple thermal and engine feed management, allowing for dedicated control, monitoring and pumping for both assets;
- The dedicated cooling fuel ducts can be sized and monitored for higher fuel mass flows and, therefore, higher total absorbed heat flows, increasing the maximum cooling potential of the heat exchanger;
- The recirculating architecture allows for heat storage inside tanks, generating progressive temperature increase, which leads to potential usage of the tanks as passive heat exchangers. In the end, this translates to a generally higher thermal endurance of the aircraft.

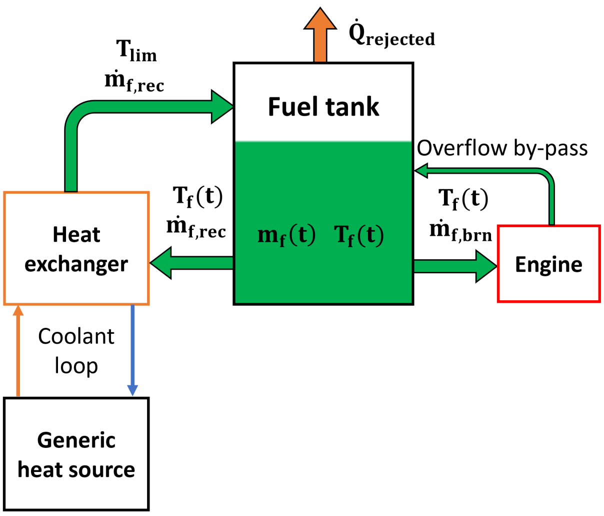

Figure 6 Fuel-based TMS with heat exchanger in parallel recirculation.

Nevertheless, the separation of the fuel heating line from the engine feed line, prevents the fluid from entering the combustion chamber at the maximum allowable temperatures. In fact, fuel sent to the engines will be at the mean temperature of the tank reservoir, which will always be lower than the temperature at the heat exchanger outlet. This aspect tends to diminish during the mission, as the mean temperature of the stored fuel rises and is thus more apparent during the initial phases of the flight. Consequently, the following hindrances could also be identified:

- The impossibility to maximize the engine-fed fuel temperature, minimizes benefit associated with combustion efficiency;
- The impossibility to maximize the engine-fed fuel temperature comports the consumption of fuel that still presents significant heat capacity to be exploited for sensible cooling. This aspect is a significant limitation to the total thermal endurance of the aircraft;
- The progressive temperature increase and fuel evaporation inside the tanks represent a relevant flammability hazard to be monitored and managed.

In the end, such an architecture is best suited for low to medium heat load management, especially in the case of elements whose activity is not directly connected to the engine functioning and may require independent or intermittent cooling. Therefore, usage of F-TMS with heat exchanger in parallel recirculation for electronic equipment cooling is currently the main application of such architectures. An example of such an architecture is provided in the Full Authority Digital Engine Control (FADEC) cooling loops described in the work of Lui et al. [97] and Ho et al. [83], while a more detailed description is proposed by Doman [82].

3.1.4 F-TMS with heat exchanger in series recirculation

F-TMS with heat exchanger in series recirculation, represented in Fig. 7, maintain the use of a dedicated pipe for thermal fuel flow return to the tank. However, in contrast with the parallel architecture, the thermal and feed lines are merged back together, with the heat exchanger being placed in series before the engine. The introduction of a valve control system downstream the heat exchanger allows for the preservation of the separate control of both flows despite the merging of the two lines. This way, the maximum required fuel mass flow amongst thermal and feed flow is provided via a single pump at the tank out-take and then passed through the heat exchanger. Fuel exiting from the heat exchanger is then split between the required amount being sent to the engines’ combustion chamber, and the remaining portion, if present, being sent back to the tank. Along the return line an auxiliary air cooler could also be introduced to increase system safety or simply to extend the overall aircraft thermal endurance provided by the TMS. Overall, the main advantages of such an architecture are:

- The reduced need for additional drag-inducing air-intakes;
- The adoption of a single fuel line may reduce the number of pipes, pumps and other components associated with the design, saving weight, costs and system reliability issues;
- The feed of fuel exiting from the heat exchanger directly to the engines, allows for achievement of maximum fuel temperature and, thus, for higher improvement of combustion efficiency;

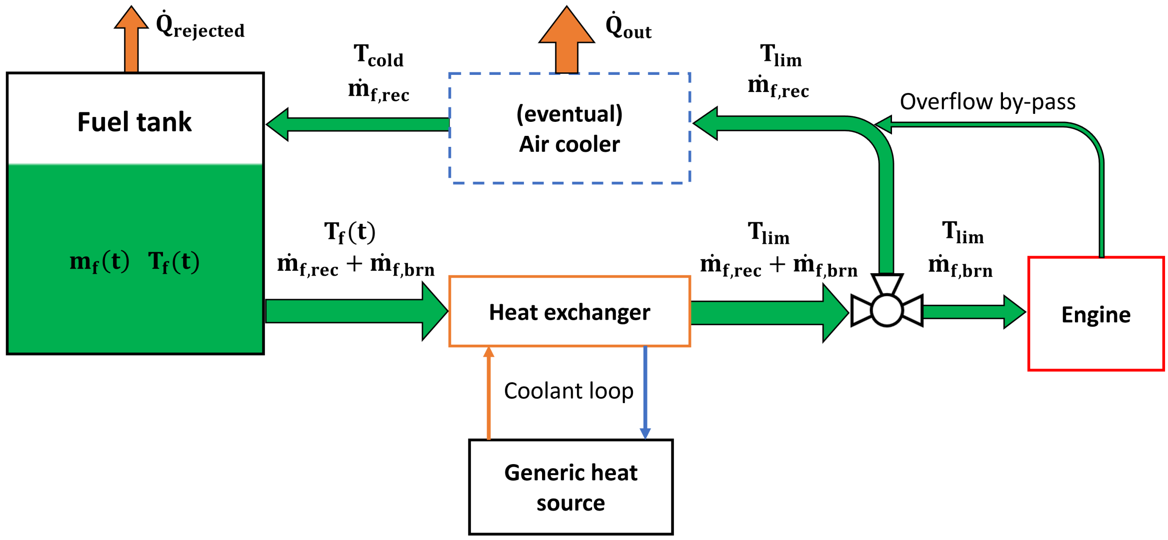

Figure 7 Fuel-based TMS with heat exchanger in series recirculation.

- The adoption of the valve control system allows for decoupling of thermal and engine fuel flow monitoring and control;
- The initial duct connecting fuel tank and heat exchanger, as well as the recirculating duct from the heat exchanger back to the tank could both be sized to account for fuel mass flows depending from the heat source needs and not the engines';
- The recirculating architecture allows for heat storage inside tanks, generating progressive temperature increase, which leads to potential usage of the tanks as passive heat exchangers similarly to the approach proposed by Kellermann et al. [57];
- The combination of recirculating architecture with series placement of both heat exchanger and engines allows for full exploitation of fuel associated thermal capacity, translating to a generally higher thermal endurance of the aircraft.

Nevertheless, the following hindrances could also be identified:

- The integrated pipeline whose flow requirements depend from more than one user, introduces the need for a reliable valve system, or other flow management device, as well as a dedicated control strategy, therefore increasing the overall system complexity;
- Integrated nature of the architecture makes it challenging to implement as an eventual retrofit, and calls for dedicated and careful design since the project phase;
- The progressive temperature increase and fuel evaporation inside the tanks represents a relevant flammability hazard to be monitored and managed.

The higher complexity of this architecture, both from a design, cost, reliability and safety point of view, relegated such a solution to advanced aircraft applications mostly, characterized by high performance requirements. In fact, challenges posed by the design always hindered its application in the market of civil transport aviation. Nevertheless, current evolution in the needs for advanced thermal management could justify the adoption of said systems.

3.1.5 F-TMS with heat exchanger in series recirculation and double tank

F-TMS with heat exchanger in series recirculation and double tank configuration, represented in Fig. 8, expand the concept of the previous design by splitting the main tank into two diverse subsystems, characterized by different purposes. The first of those components is the reservoir main tank, which is dedicated to the storage of high amounts of fuel to be kept at relatively low temperatures. Such a tank presents a single out-port from which fuel is sent to the main users, while intakes allowing for fuel return upon heating are absent. Therefore, the main tank effectively behaves like a non-recirculating F-TMS with feed-line heat exchangers and maintains its mean temperature almost unaltered along the mission. The other subsystem of the dual tank architecture is the so-called recirculating secondary tank. Characterized by a smaller capacity, said tank presents both fuel intakes and outtakes, unlike the previous one. The former allows for heated fuel in excess to reach the tank, while the latter allows for fuel extraction and supply to the various users. Therefore, this tank will be dedicated to store the hot fuel coming from the heat exchanger not being burnt in the engines. From the user point of view of the users, instead, fuel coming from both tanks will be mixed via a dedicated mixing valve, according to the current needs of the main heat sources, and then sent to the principal system heat exchanger.

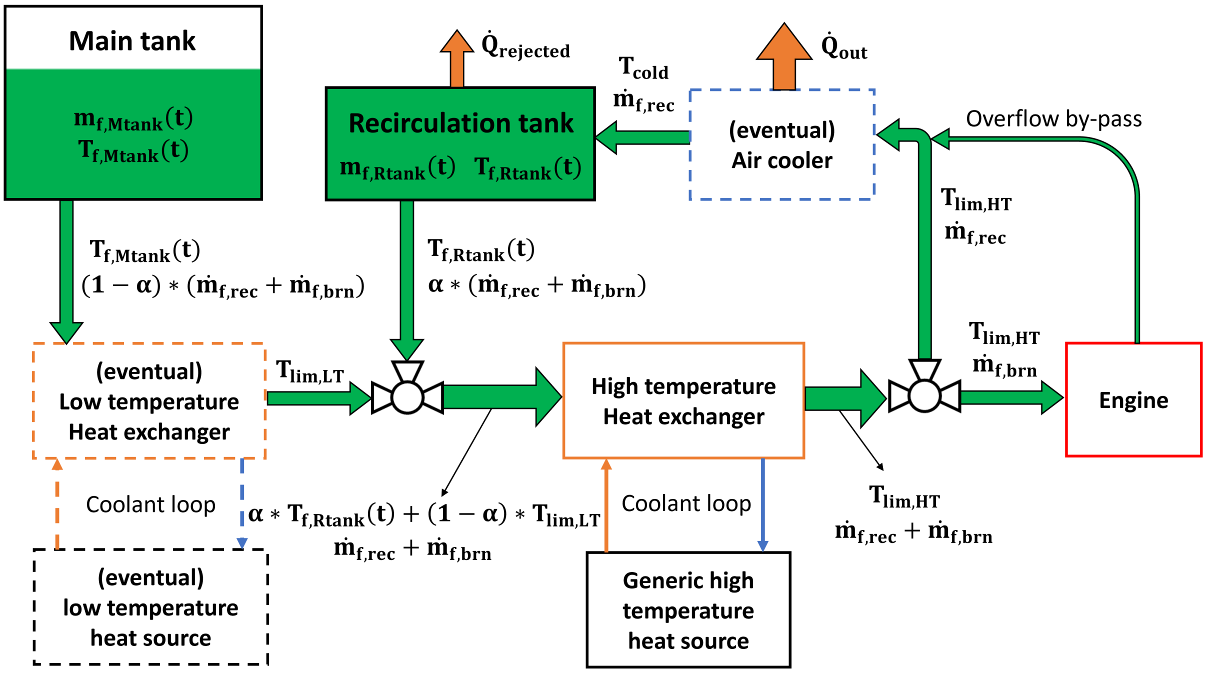

Figure 8 Fuel-based TMS with heat exchanger in series recirculation and double tank design.

The significant increase in complexity associated with the adoption of the dual tank is justified by the advantages granted by such a system, being listed below:

- The same benefits of the previous F-TMS with heat exchanger in series recirculation;
- The presence of the ”low” temperature reservoir tank allows for safer cooling of sensible components, such as electronics or batteries, via access to an, almost, constant temperature heat sink;
- The separation of the tank system into a low temperature one and a high temperature one allows for higher achievable maximum fuel temperatures. In fact, by moving upstream the mixing valve all the components characterized by the lowest allowable temperature requirements, it becomes possible to cool such components only via the low temperature fuel tank. This way, the limit mean temperature of the recirculation tank can, instead, be increased, since it is no longer bounded to the requirements of sensible components. Therefore, the exploitable thermal capacity of the hauled fuel is further incremented via augmentation of maximum allowable temperatures;
- The increase in maximum allowable mean temperature of the recirculation tank permits reaching higher temperature deltas between the external environment and the fuel itself. Therefore, the mechanism of passive heat rejection through the tank walls is favoured and the overall thermal endurance of the aircraft improved.
- The lower capacity of the recirculation tank, determines the presence of a smaller associated thermal inertia when compared to a single tank system; Consequently, high fuel temperature is reached much faster in said conditions and, therefore, benefits of presenting maximum temperature delta between fuel and external air could be exploited earlier in the flight and for longer portions of the mission.

Nevertheless, the following hindrances could also be identified:

- The separation of the fuel tanks, the introduction of the mixing valve apparatus, together with the already discussed recirculating heat exchanger architecture present significant increases in complexity of the system design and control;
- The relevant increase in system complexity determines challenging increases in costs, number of components, reliability issues and need for redundancy;
- Integrated nature of the architecture makes it challenging to implement as an eventual retrofit, and calls for dedicated and careful design since the conceptual phase;
- The progressive temperature increase and fuel evaporation inside the tanks represent a relevant flammability hazard to be monitored and managed;
- The full benefits of a similar architecture are only really exploited only if the intended TMS is supposed for to provide cooling to several heat sources characterized by varying degrees of allowable maximum temperatures.

Due to the numerous challenges associated with such an architecture, no known systems are currently adopting the ”F-TMS with heat exchanger in series recirculation and double tank” solution. In fact, despite numerous studies being conducted on the topic, especially those proposed by Prof. Doman et Al. [67, 82, 81, 80, 78], investigating its benefits and even demonstrated its feasibility via experimental validation, conceptual design still is the only current application of said architecture. Nevertheless, as proposed in the aforementioned studies, it is very likely that challenges of the next generation of aircraft will justify the adoption of similar constructions on the highest performance constructions.

4 USE CASE

The previously specified literature based results are here applied to a plausible next-gen, hybrid-electric aircraft making use of fuel cell power generation units. Due to the current state of aviation based electrification programs being mostly relegated to small scale general aviation demonstrators [14], a non-better specified aircraft in the regional transport weight class is considered as the use case of this study. Said aircraft are really common constructions for use in short range air-transport and represent one of the smallest classes of available passenger aircraft. Some typical characteristics of current regional transport aircraft, such as ATR-72-600 [101], Dash 8-400 [102], Fokker F50 [103], and Do228 NXT [104], are:

- A passenger capacity ranging from 19 to 90 PAX, depending on size and configuration of the aeroplane;
- A propulsion system consisting of two separate turbo-engines, one per each semi-wing, both driving a propeller via gearbox reduction;
- A combined total mechanical power at both propellers ranging from 1.0 to 7.5 MW, depending on the overall size of the craft;
- A maximum achievable range of about 1000 to 2000 km, at full PAX payload. However, the typical mission range of said aircraft is most often comprised between 300 to 500 km during regular operation.

These specification are therefore to be associated with the following design choices, proposed to enhance project feasibility in the optic of increasing aircraft degree of electrification:

- Adoption of a hybrid propulsion system to be powered via conventional turboprop engines, coupled with electric motors, in parallel configuration, contributing to the total torque at the propeller shaft;
- Introduction of a PEM fuel cell stack, intended to convert chemical power stored inside hydrogen tanks and to supply the electric motors.

The actual degree of hybridization, however, is left undefined since, while its maximization is definitely one of the main targets of such a project, its optimal value is not so easily defined. In fact, benefits provided by systems' electrification in components efficiency and pollutants emission reduction, are easily offset by the weight increase with respect to the elements that these systems are substituting. Variations in the hybridization degree are rendered even more crucial in the case of TMS exploiting fuel as a relevant heat sink, since any reduction of fuel reserves associated with an increase in the degree of electrification, both results in higher thermal loads being generated, as well as lower exploitable heat capacity, thus significantly impacting the overall thermal endurance of the aircraft.

4.1 METHODOLOGY

Previous sentence shows how optimized design of the TMS represents one of the key assets not only in defining the overall feasibility of the project, but also in determining its effectiveness in the effort of reducing the aviation carbon footprint. Therefore, a structured design methodology is needed to guide the development of the whole aircraft system and the TMS alike. Model Based System Engineering (MBSE) approach is chosen for this purpose. Citing the INterantional COuncil of System Engineering (INCOSE) on the matter, MBSE could be described as "The formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases."
Ample diffusion of such a methodology in the aerospace sector, as well as its demonstrated effectiveness in managing complex design development, such as an integrated fuel-based TMS, justify the adoption of the method. The associated procedure could be summarized via the so called "V-diagram", here represented in Fig. 9.

The problem is thus first identified and the project boundaries are defined. Then the whole system is progressively shaped via gradual decomposition into its various subsystems and components, increasing the level of detail associated with the design. At the end of the process, numerical simulations and tests of all relevant components

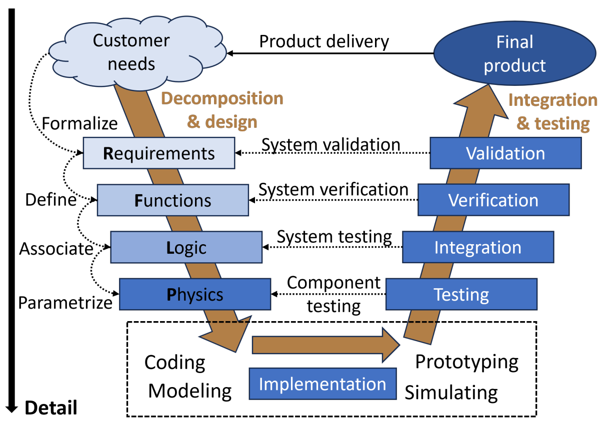

Figure 9 V-model diagram according to MBSE approach.

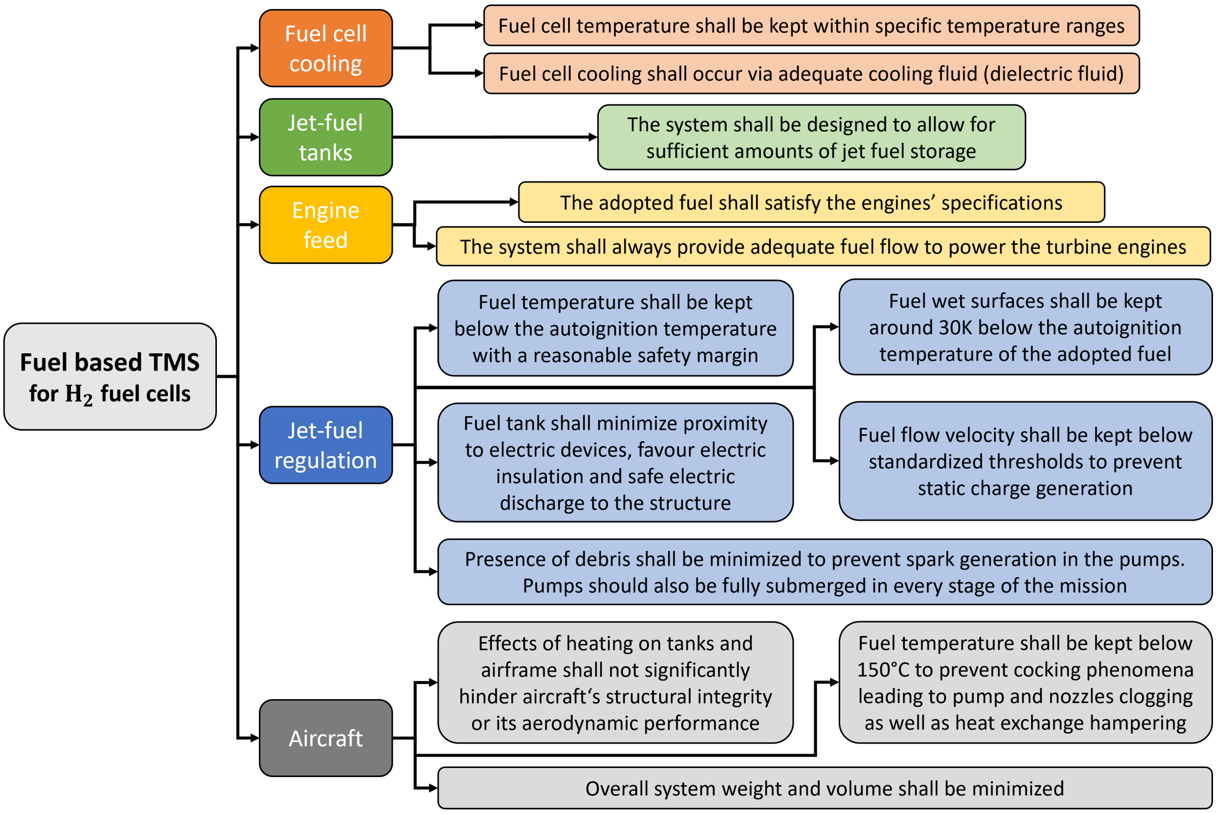

Figure 10 Main stakeholders requirements for a fuel-based thermal management system to be applied on a regional transport, twin-turboprop, parallel hybrid-electric, fuel cell powered aircraft.

are performed, completing the design phase. Later, the various components' models are progressively integrated and tested until a simulation of the global system behaviour is achieved, and the original requirements validated.
Finally, it is important to consider that, while trying to apply such a methodology, frequent iterations and revisions are suggested along the design process. This allows to verify that the final product requirements are effectively in line with the stakeholders needs as the level of detail in the modelling is increased. This is achieved by verifying that functions are properly defined and executed, that the logical elements are justified and the numerical results are in line with the expectations and coherent with the physics. An complete overview over the proposed methodology can be found in the works of Vitolo et al. [105] and Mhenni et al. [106], while the work of Pace et al. [107] provides an in depth analysis over the formalization of the system's requirements.

4.2 MBSE APPLIED TO THE USE CASE

The aforementioned methodology is therefore applied to the regional aircraft use case previously described, starting from the formalization of the intended requirements of the integrated system. Being the TMS a subsystem of the whole aircraft deliverable, the stakeholders of this study should not be identified in the final customers of the whole aircraft, yet, rather, stakeholder should be considered as the main elements that the thermal management will be expected to interface with, as well as support, satisfy and integrate. Therefore, starting from the analysis of the literature proposed architectures, it is possible to identify four main components constituting the F-TMS; those element are:

- The fuel tank, which stores the required fuel for the expected mission profile, providing it as a combustible to the engine and a heat transfer vector to the heat source. It also acts as an effective heat sink and, eventually, as a passive heat exchanger;
- The heat source, which describes the heat flux generation that will need to be managed by the integrated system;
- The engines, which define the fuel consumption profile of the aircraft, according to the mission profile, and determine the progressive depletion of fuel reserves in the tanks;
- The main heat exchanger, which is entitled with the realization of the heat transfer from the source to the fuel.
- The collection of pipes and tubes supplying the various components of the assembly represent a significant asset in the determination of the masses associated with the overall assembly and are bound to strongly influence elements placement within the aircraft. However, they are neglected

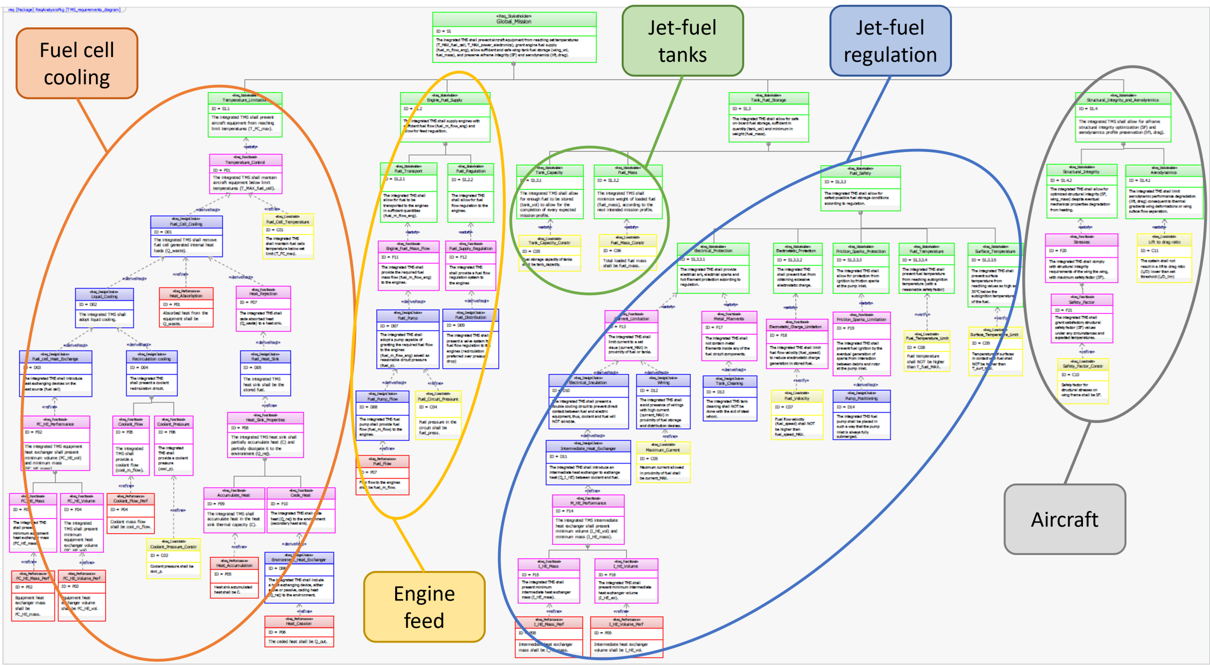

Figure 11 Preliminary requirements tree of a fuel-based TMS for hybrid-electric regional transport aircraft

for the purpose of this study, due to the preliminary nature of this study and coherently with most of the models presented in the literature, being described via lumped parameters models [57, 95, 81, 67].

Now, due to the current study being a preliminary one, and the purpose being the evaluation of the feasibility and potential of the solution from a purely thermal standpoint, the specifications of the heat exchanger, being mostly related to volume and masses constraints, could simply be translated into a global volume and mass requirement of the whole TMS. Therefore, the heat exchanger component is just integrated with the fuel cell element into a single stakeholder, contributing to the overall thermal balance as a generic resistance, describing the heat exchanger efficiency. Further analysis should investigate the properties of said elements separately in the future, with a focus towards the heat exchanger specifications.

Nevertheless, the remaining three components, clearly identify some elements which the TMS will need to interface with and that will impose some constraints and expectations on the design. Therefore, considering the use case of a regional transport aircraft, the requirements imposed by these components over the integrated F-TMS multi-functional purpose of fuel storage unit, fuel supply unit, thermal heat sink module and passive heat exchanger, were characterized as shown in Fig. 10.

However, modeling of a thermal management system subject to a progressive fuel temperature increase along the whole flight profile, comes with significant considerations on the matter of safety. Therefore, a fourth stakeholder is introduced to account for international regulations on the matter of flammability and safety while handling fuel. Specifically, the Certification Specifications for Large Aeroplanes (CS-25) [108] of the European Union Aviation Safety Agency (EASA) was taken as a reference. The most relevant guidelines, constraints and procedures expressed by said regulation on the matter of safe fuel handling, storing and heating, where thus purposefully tracked into the main requirements diagram.

Finally, some generic requirements associated with the overall interaction of the integrated F-TMS with entirety of the aircraft are also proposed. The main topics of such requirements being the limitation of system masses and volumes, the consideration of the effects of fuel heating on surrounding walls structural performance and the preservation of aircraft piping from fuel chemical precipitation and nozzle occlusion.

Both of these two other requirements are also represented in Fig. 10. Said collection of requirements is thus formalized via the use of Rational Rhapsody software and the rules of the SysML language. Some numerical values are introduced to further specify the requirements with reasonable expectations suited for an example regional transport aircraft. The previously listed stakeholder requirements are later expanded into more specific system requirements describing the various design choices, constraints and performances, leading to the formalization of the preliminary architecture; like, for example, the decision to exploit stored jet-fuel available heat capacity as a relevant heat sink for the TMS. Consequently, the waterfall of defined requirements comes to

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define the whole system requirements tree that is represented in Fig. 11. A more in depth view of the contents of the requirements diagram is also provided in Fig. 15, providing details over each single requirement

Successively, the so called "functional requirements", which introduce the functions that the system will be expected to perform once realized, are expanded, described and explained via the creation of purposefully built functional diagrams. In particular, activity diagrams are used in this case to define the sequence of actions that the TMS will be expected to perform in response to the events occurring in the external ambient, along the surrounding and interfacing systems, as well as inside the elements of the TMS itself. For a matter of simplicity, due to the great variety of actions expected to occur, as well as to avoid the repetition of identical actions inside the same diagram, the whole activity diagram of the TMS is decomposed into several sub-models. The simplest and most common actions are thus defined into brief, non-component specific sequences, while the most elaborate functions simply recall those trivial sequences via hyperlinks, preserving the overall readability of the schemes. In order to exemplify such a concept, the amplest sequence of the model is here represented in Fig. 12, with the hyperlinks to simpler functions being evidenced by the presence of a small "trident" mark in the bottom right corner of the connected block.

As anticipated, the fulfillment of said functions has to be performed via dedicated components which are not necessarily defined at the start of the design process. The definition of all expected system functions via MBSE approach allows for a clear and justified identification of all such required components, which are specified inside the logical diagrams of the systems. For the purpose of this study, two different diagrams where utilized, a Block Definition Diagram (BDD) and an Internal Block Diagram (IBD). The former is used to define the dependencies of the various identified components from their reference subsystems, as well as the dependencies of those subsystems from the whole TMS. The latter, instead, is used to specify the logical interfaces established amongst the various components as well as the identification of those variables that are relevant for the sizing of the components, and the associated functions. Such variables can further be classified into "local variables" and "global variables". The former being dedicated to the description of a single component's behaviour. The latter intended for the description of the whole TMS performance, its validation with respect to the design requirements, and data transfer between different models and submodels. This classification allows for proper compartmentation of the model variables, favouring flexibility in the use of the submodels, enhanced readability of codes and diagrams, and generally lower computational costs, via the minimization of the amount of variables being transferred from one model to the other and the possibility to

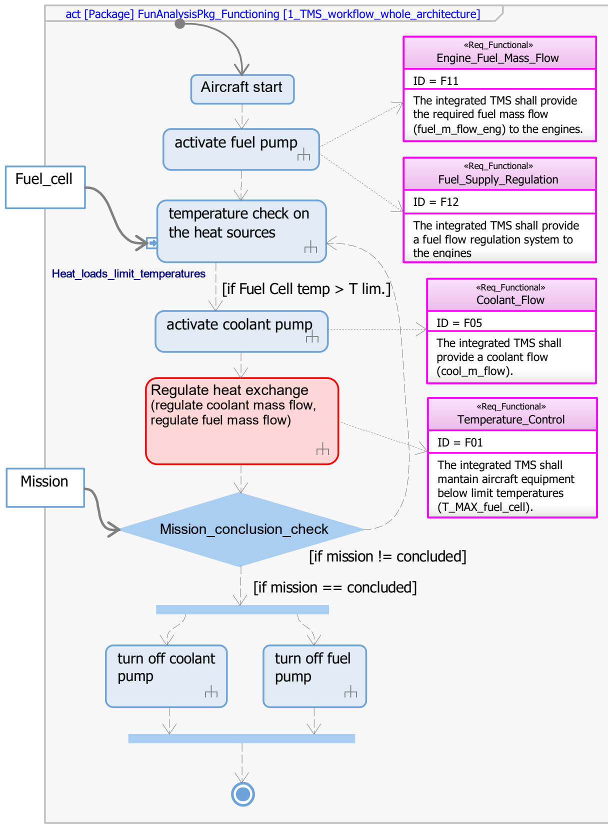

Figure 12 Activity Diagram describing the aircraft TMS activation cycle till mission conclusion

easily develop Reduced Order Models (ROM). The "fluxes" describing how the values contained in such variables are exchanged between the various components are also defined, providing a preliminary structure to any design, sizing or testing model of interest. A representation of the developed IBD of the fuel-based TMS is shown in Fig. 13.

It is interesting to note that, in the presented Internal Block Diagram, the aircraft engines are considered as being part of the system's heat sinks. This is due to the fact that, as stated by Manna et al. [65], any heat absorbed by the fuel being sent to the engines is effectively rejected into atmosphere through the exhaust gases. However, as the F-TMS can not influence the expected engines' fuel consumption and requirements, it is suitable to place such components outside of the collection of elements suited for sizing and optimization of the thermal management system.

Another interesting aspect that could be extrapolated from this diagram is the necessity to interpose a secondary coolant loop between the fuel cell and the fuel heat sink, which will receive heat indirectly via an intermediate heat exchanger. This is necessary to satisfy the fuel cell side requirement for the use of a specific coolant type suitable for the component, as well as the fuel safety regulation for the limitation of fuel proximity to electricity sources.

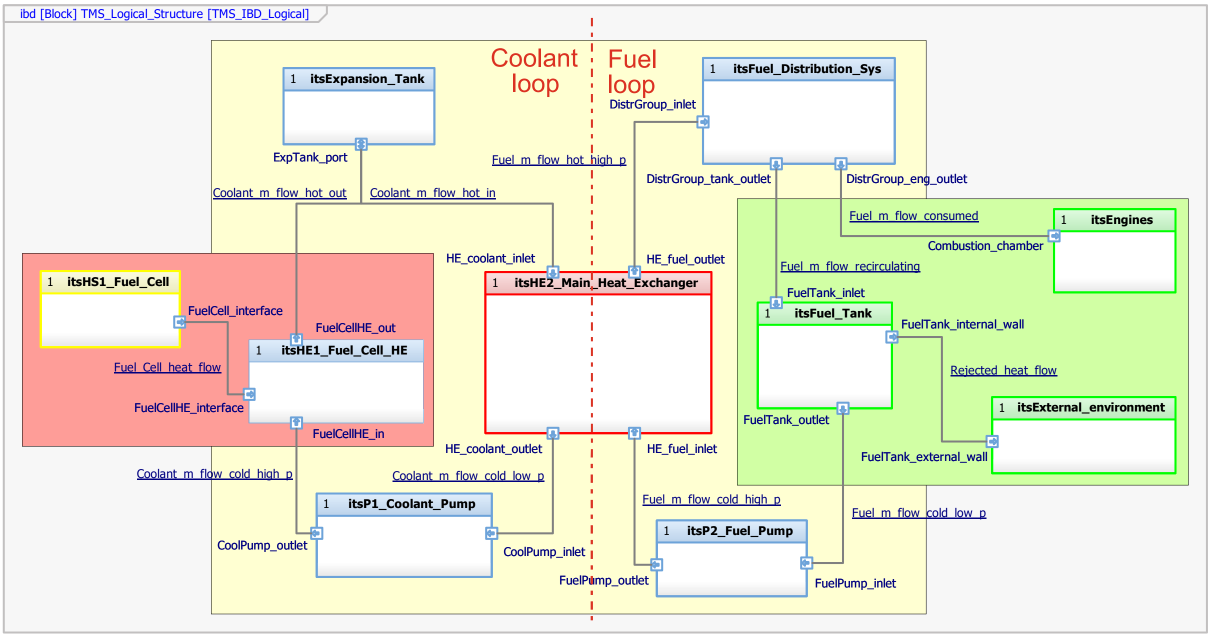

Figure 13 Internal Block Diagram of a fuel-based TMS for hybrid electric aircraft. Red square contains elements acting as heat heat sources; green square contains the heat sinks; yellow square contains elements of the TMS that require sizing and optimization, overlapping, in some cases, with with the other two squares, per the fuel cell heat exchanger, and the fuel tank.

Each logical element of the diagram is finally characterized through the definition of a series of logical variables describing the main parameters intrinsic with the modelling of said element. These parameters shall act as the main properties to be evaluated and tracked throughout the numerical simulation of the component. Some relevant examples of these variables are: the waste heat of the fuel cell $\dot{Q}_{waste}$, and its instantaneous temperature T_{FC}; the main heat exchanger temperatures $T_{HE_{cool,in}}$, $T_{HE_{cool,out}}$, $T_{HE_{fuel,in}}$, $T_{HE_{fuel,out}}$ and its associated mass m_{HE}; and also the tank stored fuel mass m_f and temperature T_f.

A series of flow variables are also defined to track parameters exchanged between the various elements of the IBD diagram via the links connecting the various proxy-ports. Most notably, the instantaneous fuel cell temperature T_{FC} and the heat extracted by the heat exchanger connecting the fuel cell to the coolant loop $\dot{Q}_{HE-FC}$; the coolant mass flow imposed by the coolant pump $\dot{m}_{pump_{cool}}$ to the fuel cell heat exchanger and its associated temperature $\dot{T}_{pump_{cool,out}}$; or the fuel mass flow sent by the fuel distribution systems to the engines $\dot{m}_{f,brn}$ and to the tanks $\dot{m}_{f,rec}$.

The last step of the descending branch of the V-model involves the translation of the IBD into a numerical simulation model. This involves the formalization of the physical correlations describing the behaviour of the various logical elements and the association of a representative numerical value to each of the defined logic variables. The actual realization and description of the numerical models is left for future investigations and will be subject of further studies by our research team. However, a few relevant numerical values can here be anticipated accordingly to the specifications of fuel cells, and regional transport aircraft, taken from the literature. These include: a limit operating temperature of the fuel cell of $T_{FC_{lim}} = 80$ °C, assuming LT-PEM; a maximum fuel cell waste heat production of $\dot{Q}_{waste} = 800$ kW, roughly equivalent to a 20% degree of electric-propulsion hybridization for a medium power regional transport aircraft. An initial tank fuel temperature of $T_f = 40$ °C, assuming the fuel to be in equilibrium with the external environment in hot day conditions.

Diversification of the presented logical model for the formalization of each of the 5 different configurations discussed in Sect. 3.1 shall also be be the subject of future analyses, along with their numerical implementation. Tradeoffs between the cooling potential and corresponding system complexity introduced by each architecture shall be addressed specifically for the intended application, via numerical simulations of the performance and confront with the requirements. Aspects such as the extracted waste heat, the system associated thermal endurance, the fuel preheating prior combustion, the passive heat rejection through the tank walls shall be compared.

In conclusion, a preliminary representation of the proposed fuel-based Thermal Management System is provided in Fig. 14. There a schematic view comprising the elements extracted from the Internal Block Diagram of Fig. 13 is

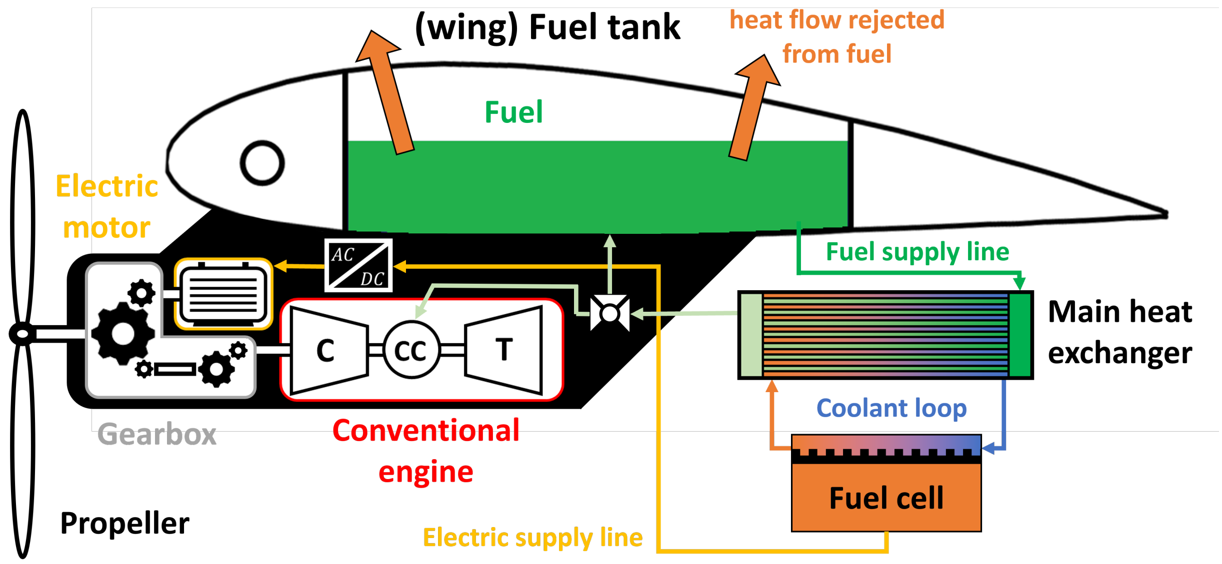

Figure 14 Fuel-based thermal management system scheme and main components for a regional transport aircraft adopting a parallel hybrid-electric propulsion supported by twin-turboprop engines and asynchronous electric motors powered trough fuel cells (not-to-scale).

provided, along with their integration into a parallel hybrid-electric propulsion configuration for a regional transport aircraft.

5 CONCLUSIONS

The results of this study evidence how the development of innovative thermal management systems for the aerospace represents a crucial asset in the design of next generation aircraft. This trend is driven by several factors, with the ever-increasing amounts of installed electric and electronic equipment being the most prominent. In particular, the adoption of fuel cells for power supply of electric motors in hybrid-electric propulsion architectures appears as a most challenging topic, mainly due to the relevant amounts of waste heat being produced by such components.

A number of different cooling solutions are presented in the literature as potential candidates for addressing this growing issue. These solutions could ultimately be classified into three separate categories, depending on the adopted reference heat sink.

- The air-based solutions. These employ external atmospheric air to provide component cooling and are, arguably, the most widespread designs due to their effectiveness, safety and simplicity;
- The Fuel-based solutions. These exploit the intrinsic thermal inertia of fuel to absorb heat from a reference heat source. Typically less prominent than air-based designs, fuel-based solution are still relatively common, thanks their convenience in cooling component that are close to the engines, and the added benefit of improved exploitation of the fuel resource. Five different F-TMS architectures are here described in detail according to the literature;
- The alternative heat sink solutions. These represents a collection of very different designs, including phase change materials and chemical heat sinks. Alternative heat sink are often limited to some niche applications, due to their reduced thermal capacity and being best suited for peak heat load management.

Amongst these three classes, air-based solutions, and especially ram-air, have been thoroughly investigated in the literature. However, issues associated with the induced drag introduced by the ram system have been shown to represent a major detriment to cooling the low temperature ($60 - 80$ °C) high waste heat production ($\varepsilon \approx 50\%$) associated with fuel cells.

The exploitation of the thermal inertia associated with fuel stored within tanks is thus suggested in this work to support fuel cell cooling in the context of hybrid-propulsion electrification for regional transport aircraft. Advantages introduced by the integration of the fuel system into the cooling loop of aircraft components are numerous. These include: a higher heat transfer coefficient compared to air, leading to lower required mass flows and more compact heat exchangers; a direct control over the supplied mass flows through the fuel pumps; an increased independence of the system from external conditions, factors, and parameters; a better exploitation of an already available resource.

Nonetheless, F-TMS also present a series of issues and challenges that need be effectively addressed for the system to perform effectively and safely. In fact, the intrinsically

limited heat capacity of stored fuel prevents this element from behaving like an ideal thermostat. Consequently, the fuel temperature is bound to increase throughout the mission up to a set limit threshold, which defines the ”thermal endurance” of the system, and influences the maximum range of the aircraft. The resulting rise in fuel temperature also introduces a significant flammability hazard, which is further aggravated by the concurrent increase in fuel evaporation. This demands for both phenomena to be carefully tracked and managed, as well as for the adoption of a fuel tank inerting system.
Moreover, the adoption of a F-TMS, specifically intended for fuel cell cooling, also demands for the introduction of adequate electrical protections. These are meant to prevent electric discharges from propagating into the fuel system, leading reduced fuel cell efficiency and tank flammability hazards. The introduction of an intermediate coolant loop preventing direct contact between the jet-fuel and the fuel cells is thus required, along with the integration of a deionization filter within said loop.
Finally, the inevitable increase in system complexity when designing such an integrated architecture is addressed through the tools of the MBSE. Requirements analysis of the intended fuel-based TMS is hence proposed for the specific use case of an hybrid-electric, fuel cell powered, turbo-propeller driven, regional transport aircraft, and accounts for all major system needs expressed in the literature. A preliminary functional analysis is later conducted, leading to the formalization of the system's logical architecture, which is represented using an Internal Block Diagram. Said diagram is finally employed to define the various system parameters required for the modelling of the F-TMS and its subsequent numerical simulation.
The next phases of this study will focus on translating the proposed MBSE diagrams into an actual numerical model for the simulation of the F-TMS performance and the assessment of its feasibility. Future studies shall then expand the proposed logical framework for the formalization all five reference F-TMS architectures, and later convert them into numerical models for performance comparison.

DECLARATION OF COMPETING INTERESTS

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.

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APPENDIX

A Complete representation of the F-TMS requirements diagram is provided in the following, Fig. 15.

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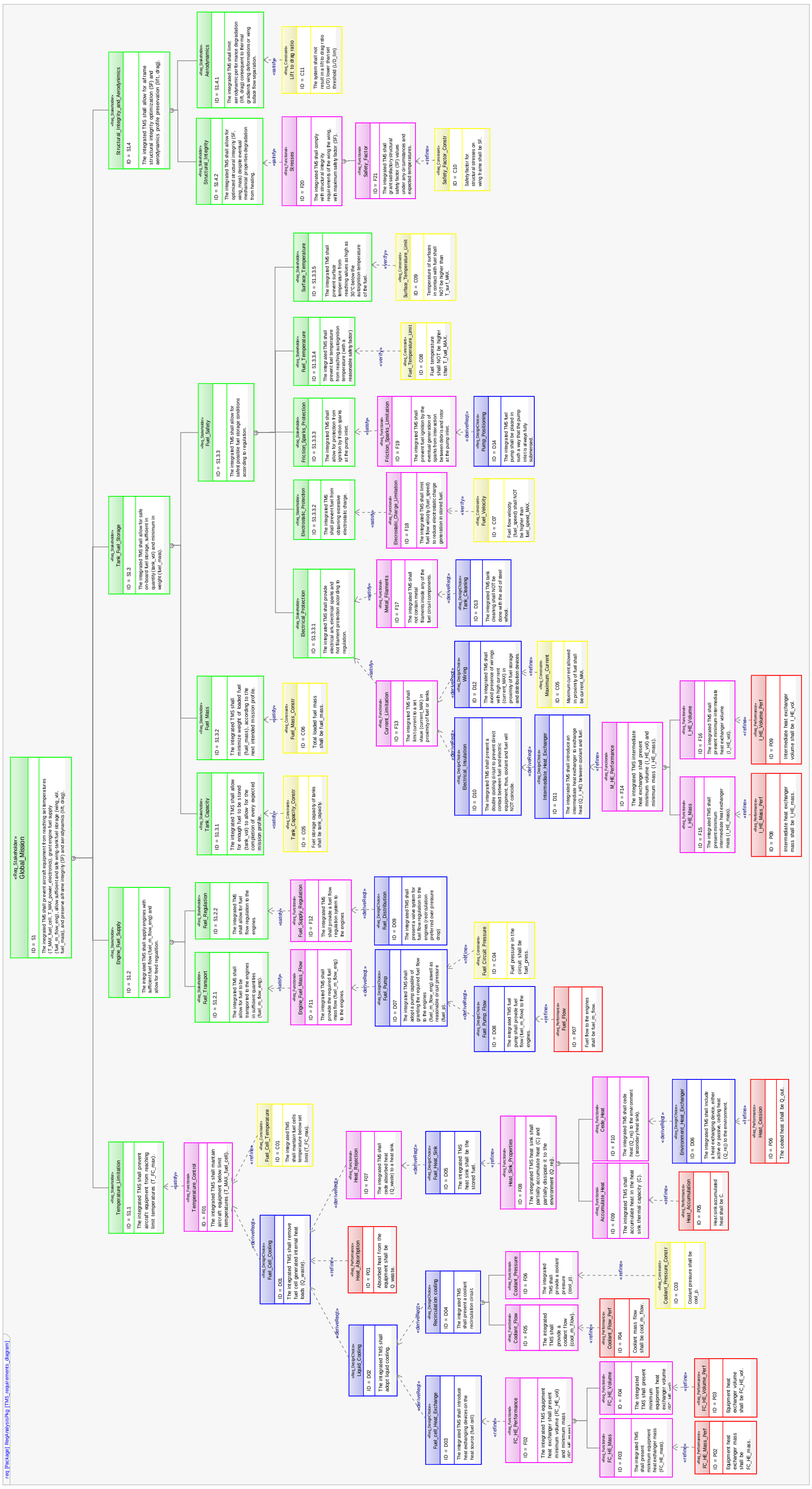

Figure 15 Complete requirement diagram of a F-TMS for fuel cell cooling on hybrid-electric regional transport aircraft.