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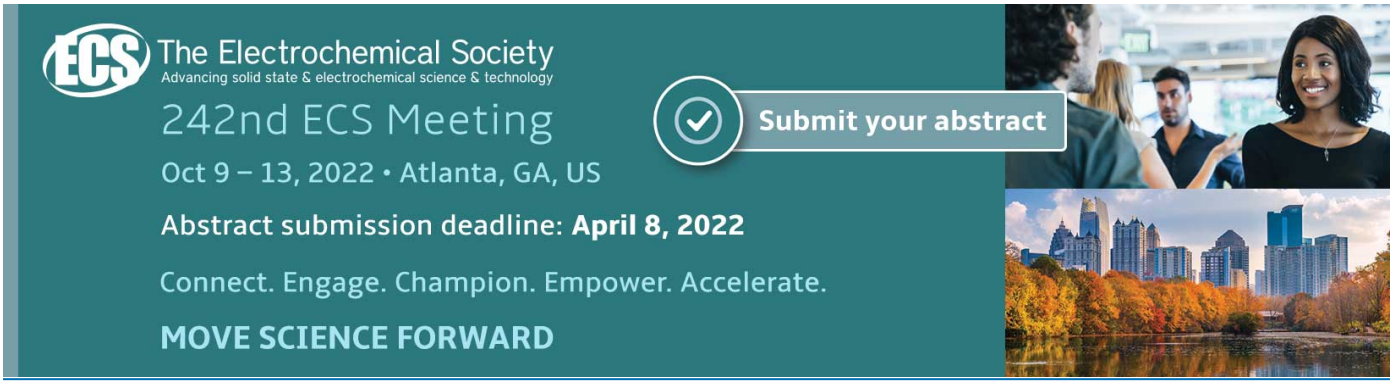
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System architectures for thermal management of hybrid-electric aircraft - FutPrInt50

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Abstract. Electric and Hybrid-Electric Aircraft (HEA) propulsion system designs shall bring challenges at aircraft and systems level, mainly in propulsion, electric and thermal management systems (TMS). The electrification of the propulsion system relies on large and high-power electrical equipment (e.g., electrical motors, converters, power electronics, batteries, and others) that dissipate heat at a rate at least one order of magnitude higher than conventional propulsion aircraft systems. As a result, high impacts on weight, drag and power consumption of the TMS/cooling systems at the aircraft level are expected. This paper proposes potential technologies to perform the thermal management of future electric and HEA, in the context of FUTPRINT50 project. For each technology, relevant aspects such as its integration to aircraft, safety, operational and maintenance impacts, certification, technologies readiness level (TRL) and the latest research works are analysed. A quantitative comparison of the several technologies is also proposed considering weight, volume, electric power consumption, pneumatic air flow and cooling air flow per cooling effect. Lastly, we present a set of potential TMS architectures for HEA.

1. Introduction

Recently published important reports, such as *AR6 Climate Change 2021* [1], already brought up the evidence of human influence on climate change. In order to minimize impacts on biodiversity and to control the green house effect, many industry sectors are setting strict requirements on the emission of gases on the atmosphere, and the aviation industry, naturally, follows this trend.


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Currently, aviation is responsible for approximately 2% of global CO_2 emissions [2], but, as the global air traffic is in constant growth, these emissions are expected to increase. Moreover, other gases with detrimental impacts on climate change are also emitted during aircraft operations, such as sulphur oxides (SO_x), nitrogen oxides (NO_x) and water vapor [3]. That makes aviation an important player on the pursuit for a sustainable future. Under the same effort, the FlightPath 2050 report [4], for example, came up with several environmental goals for aircraft operations on Europe, linked not only to emissions, but also to noise pollution. The report sets the concerning with environment and life quality as an essential part of any aeronautical project in the continent from now on.

In this context, FutPrInt50 project emerges as an important initiative to address solutions to the technical challenges that aerospace industry will face to achieve those strict operational environmental goals. It aims to develop a synergetic hybrid-electric aircraft (HEA) to transport up to 50 passengers, with entry in service expected by 2035/2040 [5].

One of the most challenging technical issues in HEA is how to manage the heat generated during its operation, since the electric and electronic equipment from the hybrid-electric propulsive architecture requires a great amount of power to work. This results in very high heat dissipation [6], and removing this residual heat from the aircraft may have significant impacts in weight, drag, electric power consumption and costs, putting in risk the concept's feasibility. The system responsible for rejecting this dissipated heat is the *thermal management system* (TMS), and in a formal definition, it aims at managing the heat transfer between heat sources and sinks to control the temperature of aircraft subsystems/components in order to achieve comfort, safety and efficiency.

As TMS is essential to HEA feasibility, FutPrInt50 project is also committed to study it. Some previous results had already been achieved and are described in [6]. They consist on a high level selection of potential cooling technologies to compose TMS and their respective TRLs (Technology Readiness Level). This paper focus on advancing from those previous results to develop conceptual TMS architectures to HEA.

2. Cooling Technologies Methodology Research

In order to advance on this research, it was essential to grasp the integration of the cooling technologies described in [6], not only for designing the TMS architectures in a proper way, but also to achieve greater efficiency. Invariably, this would require a deeper knowledge of the selected cooling technologies, their main characteristics, safety issues, common working fluids, modeling challenges, and others. Thus, the team focused on methodically acquiring this key information, through a *Cooling Technologies Assessment Sheet*.

All information provided to the sheet came from public information and FutPrInt50 participants' experience. The main qualitative and quantitative information obtained on this sheet are presented in topic 3.

3. Results and Discussion

3.1. Qualitative Data

Since many studied technologies have a low or medium TRL (lower than 6), several questions were still to be answered about them in terms of aircraft impact on operational routine at airports, integration impact on other aircraft subsystems, safety, maintenance, and others. Moreover, as the schedule is a mandatory restriction of any engineering project, it was also important to understand the consortium experience on the evaluated technologies. This could define specific TMS architectures as more or less challenging, depending on the partners previous knowledge on it, for example.

The qualitative information gathered on the *Cooling Technologies Assessment Sheets* are a first attempt to clarify some of those questions, classifying each cooling technology in

terms of reliability (presence or absence of moving parts and/or a more frequent necessity of maintenance), aircraft operations and integration impact and consortium experience. The compliance of each technology with the REACH regulation was also analysed, but no potential conflicts were identified. The research results are shown on table 1.

Table 1: Qualitative information of the considered cooling technologies.

Potential TMS Technologies	Reliability	Aircraft Operations Impact	Aircraft Integration Impact	Consortium Experience
Absorption Refrigerator	Medium	High	High	Low
Air Cycle Machine	High	Low	High	High
Forced Air Cooling	High	Low	Low	High
Joule-Thomson Effect	High	High	High	Low
Liquid Cooling	High	Low	High	Medium
Magnetocaloric Effect	Medium	High	High	Low
Passive Devices	High	High	High	Medium
Phase Change Materials	Medium	High	Low	Low
Skin Heat Exchanger	High	High	High	High
Vapour Cycle System	High	Low	Low	High
Vortex Tube	High	High	High	Low
Thermoelectric Effects	High	Low	Low	Low
Cryocooling Systems	Medium	High	High	High

3.2. Quantitative Data

The quantitative data gathered helped the team to have a glimpse on the weight, volume, electric power consumption, bleed air consumption (pressurized air extracted directly from the gas turbine) and cooling air consumption (commonly called ram air) of each technology, in relation to a certain amount of cooling capacity. These proportions, presented on figures 1 and 2 and , are essential to make an initial comparison between the technologies and a simplified analysis of their feasibility.

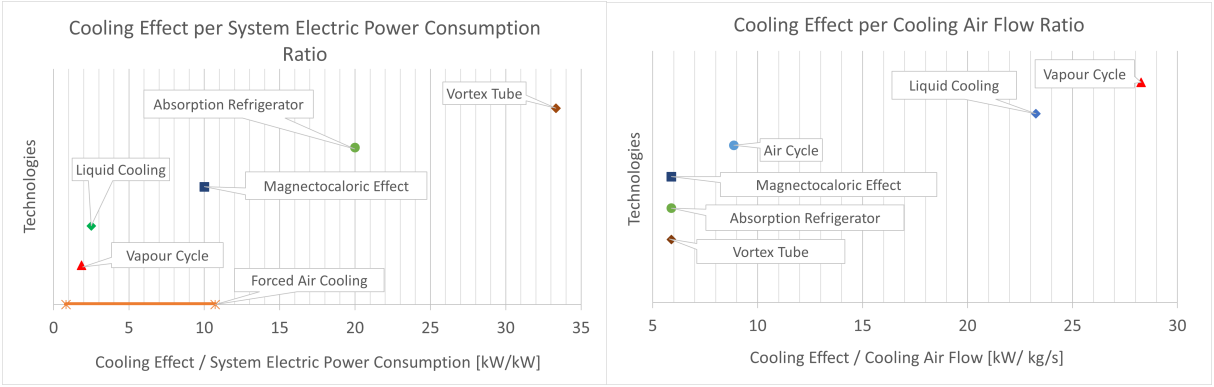


Figure 1: Cooling effect by system electric power consumption (left) and cooling air flow (right).

The lines on the graphs represent a possible variation of the ratio depending on the designed system. So, for example, in figure 2, the forced air cooling line represents the large number of fans available in the market that can have higher or lower ratios of cooling capacity by weight.

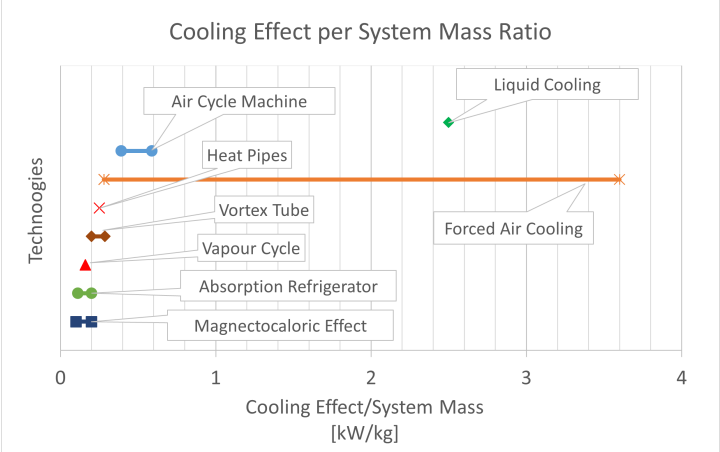


Figure 2: Cooling effect by system mass ratio

It is worth mentioning that these ratios are highly dependent on the selected application, and not all of the studied technologies have prototypes implemented on aeronautical environment. This fact adds an important uncertainty to the collected ratios. For example, the magnetocaloric effect data exposed here was collected from prototypes of magnetic refrigerators that may not be adapted to aeronautical use. Using a magnetic refrigerator in an aircraft could require additional systems that may result in higher weight for example, and this additional weight will not be appropriately represented on magnetocaloric effect line in figure 2.

Moreover, these numbers were collected on current prototypes and/or models and they do not take into account possible future improvements. The data shown are derived mainly from references [7], [8], [9], [10], [11], [12], [13], [14] and [15].

3.3. Conceptual TMS Architectures Proposed

From the technologies in [6] and table 1, five TMS conceptual architectures were developed (topic 3.3.1 to 3.3.5), based on different hybrid-electric propulsion concepts that have been studied in FutPrInt50 project: sustainable aviation fuel (SAF) gas turbine (GT) with electric motor (EM) in parallel (figure 3 left); liquid hydrogen fuel cell and electric battery in series (figure 3 right); and liquid hydrogen gas turbine - that can be driven by electric motors - in parallel with another set of electric motors, fed by a battery pack in series with a liquid hydrogen fuel cell (figure 3 centre).

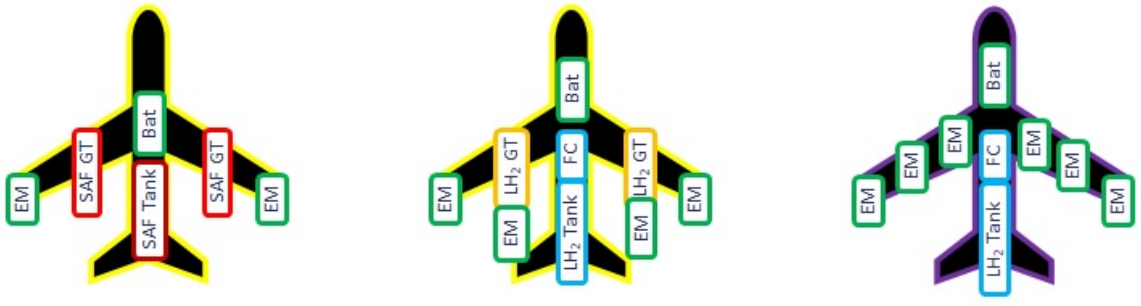


Figure 3: Proposed propulsion concepts.

3.3.1. Embraer - Liquid Cooling with Vapour Cycle The architecture shown in figure 4 is an integration between a liquid cooling loop (with ethylene glycol and water mixture

as working fluid) and a vapour cycle system (VCS) (that uses R134a as working fluid). The heat load represents conceptually a heat input in the system, but physically it can be a set of components such as electric motors, electronic speed controllers (ESC), batteries, among others, that dissipate heat during operation. As the ram air flowing around the skin heat exchanger (SHX) has a limited cooling capacity, the vapour cycle system is responsible to remove the remainder of excessive heat from the EGW (ethylene glycol and water mixture) through the evaporator. The heated R134a is, then, cooled at the condenser by the air admitted at the inlet (possibly with a NACA shape). This system is mature and has already been implemented in the aerospace industry. As a drawback, it requires a complex control in order to modulate the compressor electric power input, as it should begin to operate when the SHX is not capable of rejecting all the heat.

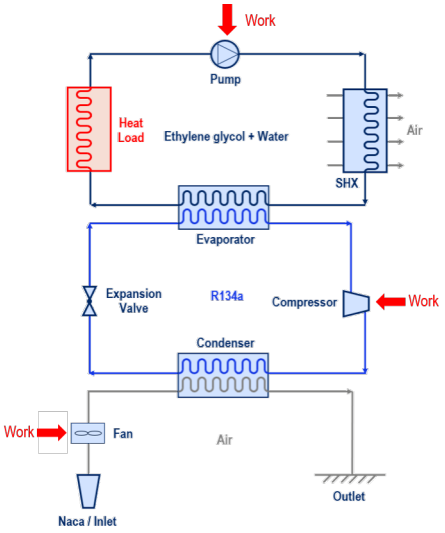


Figure 4: TMS conceptual architecture based on liquid cooling.

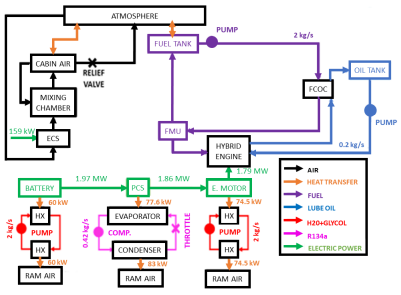


Figure 5: TMS conceptual architecture based on liquid cooling and VCS.

3.3.2. Cranfield University - Fuel-Oil Heat Exchanger A liquid cooling system is a potential alternative to cool down power electronics of future hybrid-electric propulsion aircraft systems. It consists of a closed loop where a water mixture absorbs heat from the power electronic through a heat exchanger (HX) and dumps the heat overboard using ram-air or another cooling loop. Its main benefits are the simplicity and weight of the system in comparison to the vapour cycle. An integrated concept of fuel-oil loop, liquid cooling and VCS is seen in Figure 5.

This TMS architecture takes advantage of an air cycle machine to keep comfort in the cabin, a vapour cycle (R134a) to cool the power electronics and three liquid cooling loops to refrigerate the battery, electric motor and the engine. While the electric components are cooled by the classic EGW (ethylene glycol and water mixture), the liquid loop that cools the engine uses its own oil as working fluid. The oil rejects the heat to the fuel through a fuel-oil heat exchanger, while all the other architecture loops reject the heat directly to ram air. An important advantage of this architecture is the possibility of improving the combustion efficiency by heating the fuel. However, the heating of the fuel could lead to the necessity of using an inertization system, which can add weight and a greater complexity to the whole aircraft.

3.3.3. GosNIIAS - Absorption Refrigerator The integrated cooling system indicated in Figure 6 proposes the use of an absorption refrigerator to cool the aircraft power electronics and the pressurized cabin. The absorption refrigerator contains a binary mixture in which the refrigerant has a lower boiling point compared to the absorbent. The heat provided by the gas turbine engine (GTE) by direct exchange causes the refrigerant to partially evaporate, and it enters the condenser under high pressure, where it is cooled by blowing air and turns into a high pressure liquid state. After passing through the TXV (thermal expansion valve), there is a sharp decrease on the refrigerant pressure and its evaporation begins, which continues in the evaporator.

The cooling effect from the evaporation process can be used to cool the secondary heat carrier (an ethylene glycol water mixture, for example), which will absorb heat from the power electronics and the pressurized cabin. Considering a scenario where a VCS is the main responsible for the cooling of cabin air, the absorption refrigerator will decrease the VCS evaporator heat load, and consequently, the compressor electric consumption. The secondary heat carrier may need additional cooling by means of the ram-air/liquid heat exchanger, which can be used as the only cold source of the architecture at a sufficiently low external temperature.

3.3.4. Embraer - Hydrogen The TMS described in Figure 7 was developed taking into consideration the use of a hydrogen fuel cell as part of the propulsion system, in series with electrical propulsion. The liquid hydrogen (LH2) is stored at cryogenic temperatures but needs to reach the fuel cell (FC) in the correct temperature, that depends on the FC type [16] [17]. Hence, it must exchange heat with the EGW (ethylene glycol and water mixture) at the HX/Evaporator before reaching the cell. Constant pressure must also be ensured at the FC for its correct operation [16]: this can be achieved by bleeding part of the compressed air from the cabin to the cell.

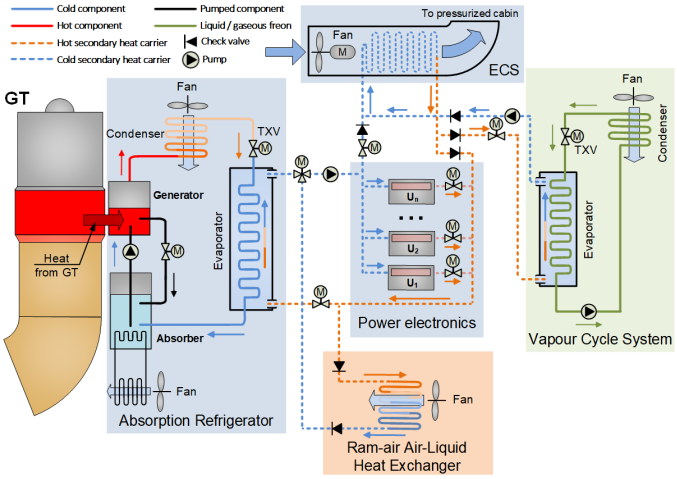


Figure 6: TMS conceptual architecture based on an absorption refrigeration cycle.

The EGW that flows through the HX/Evaporator is distributed through a manifold to a set of different pipes: one that goes to the fuel cell and a set that goes through an evaporator before being forced through the electronics, batteries and electric motors.

3.3.5. MAI - Cryo Cooling Cryocooling refers to all cooling systems that achieve cryogenic temperatures (65 to 75 K). They can be based on Stirling, Gifford McMahon or Joule Thomson cycles and are used mainly with high temperature superconducting (HTS) components, which can achieve a state of superconductivity (severe decrease of electrical resistance) when exposed to these cryogenic temperatures. A potential gain of using cryocooling would be a weight reduction related to aircraft electrical components (such as electric motors and cables), by exposing it to temperatures that could decrease significantly their electrical resistance. With less electrical losses, the size of these equipment could be reduced. As hydrogen for power generation is stored under low temperature and high-pressures, it reaches temperatures that make it adequate for cryocooling. An example of an experimental setup for cryocooling based on the reverse Brayton cycle is shown on Figure 8.

The fluid is compressed at compressor K_1 and goes through the heat exchanger AT_1, where its energy is extracted by a refrigerant. It then goes through two other sets of compressors and heat exchangers (K_2 - AT_2 and K_3 - AT_3) before going inside the recuperative cooling thermal unit (TA_p). Finally, the fluid expands and loses energy (as work) at the turbine T_D, absorbs the heat load (Q) at the exchanger TA_H and flows back into the recuperative unit before re-starting the cycle at compressor K_1.

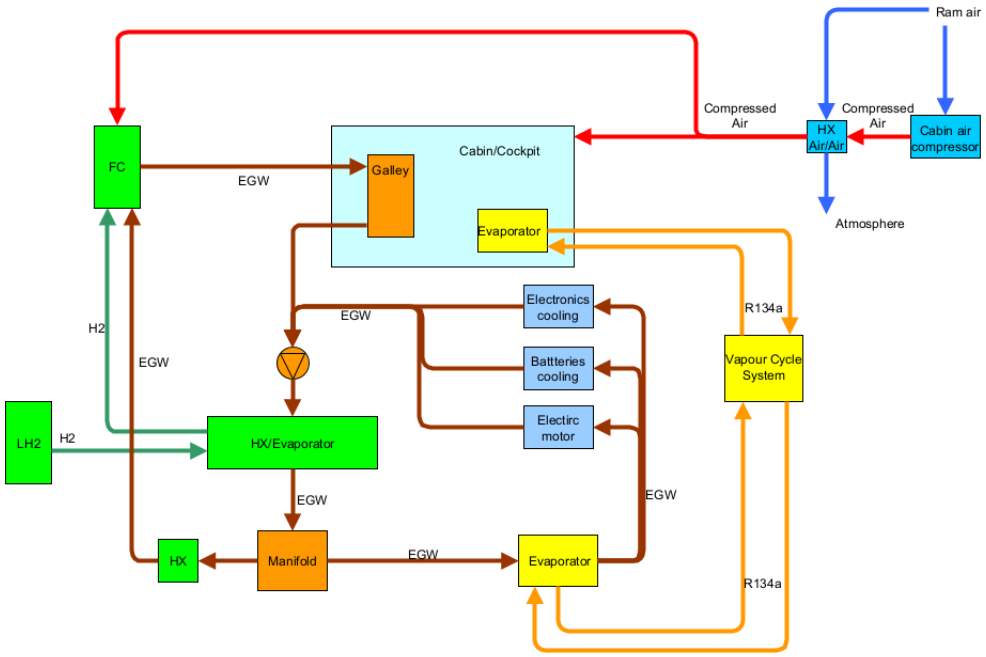


Figure 7: TMS architecture based on a liquid hydrogen (LH2) fuel cell.

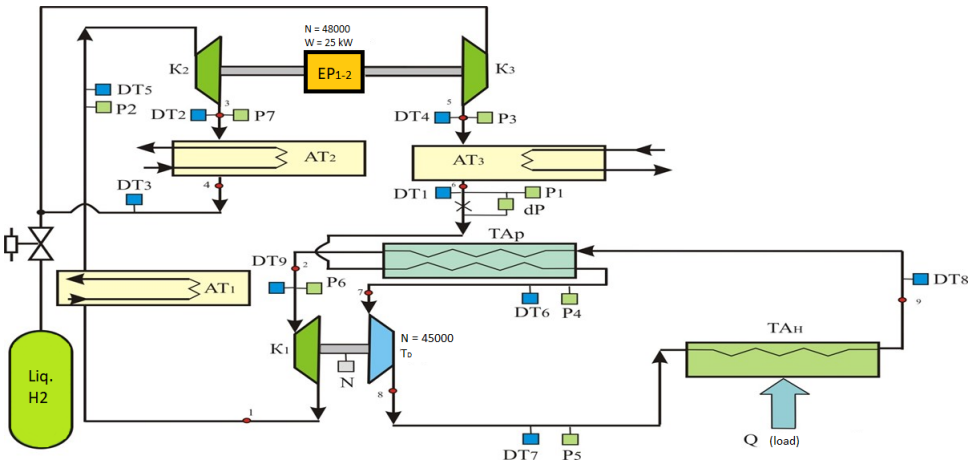


Figure 8: Cryocooling system based on the reverse Brayton cycle.

4. Conclusion

Thermal management systems architecture and features will be highly dependent on the propulsion concept adopted for each aeroplane. There are still many unknowns: from what propulsion type will be more adequate to the mission proposed, to integration challenges that have not yet been predicted (unknown *unknowns*). In addition, applications of these technologies to the aerospace sector are still emerging and, therefore, some technologies are still not mature enough. Likewise, the regulatory agencies are working on special conditions and/or means of compliance capable of embracing these new systems without compromising flight safety.

Future work will focus on modelling and simulation of the proposed architectures at system and aircraft levels. In order to do this, the aircraft propulsion system requirements are being developed and are essential to the assessment of the conceptual architectures.

Once more mature TMS architectures have been established, it will be possible to clarify the suitability of the thermal systems and their main weaknesses and strengths. Having done it, the complexity of the computational models will be increased and, eventually, integrated to an aircraft-level simulation environment in SUAVE [18].

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