Thermal Management challenges for HEA – FUTPRINT 50

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Abstract. Electric and Hybrid-Electric Aircraft (HEA) incorporate new systems, which demand an integration level higher than classical propulsion architectures systems do. High power electrical motors, converters, batteries or fuel cells, and distributed propulsion, all introduce new kinds of heat sources and dynamics that have to be accounted for and regulated. The latent opportunity to explore synergies among these systems requires the development of new models and their coupling with multi-disciplinary design optimization (MDO) toolchains. Also, an understanding of the implications into aircraft operations and trade-offs are critical to evaluate and validate gains at the aircraft level. This paper provides a definition of thermal management and functions of thermal management system (TMS) in aircraft, HEA thermal management challenges, main opportunities, conclusions and the way forward. A discussion of road ahead, regarding development of capabilities to support the design of TMS will be brought to the fore along the project, showcasing the open approach of FUTPRINT50 to be driven by open collaboration in order to accelerate the entry into service of this type of aircraft.

1. FUTPRINT50 project

The FUTPRINT50 project will contribute to the Europe environmental goals set in FlighPath2050, preparing the roadmap for a hybrid-electric regional airliner , with up to 50 passenger capacity and hybrid electric propulsion, by means of a synergetic configuration design that will surpass the efficiency and environmental performance of the current generation of regional aircraft. Figure 1 illustrates the high level requirements for the performance of the case study aircraft (on the left), and its challenging high level requirements regarding noise and emissions (on the right).

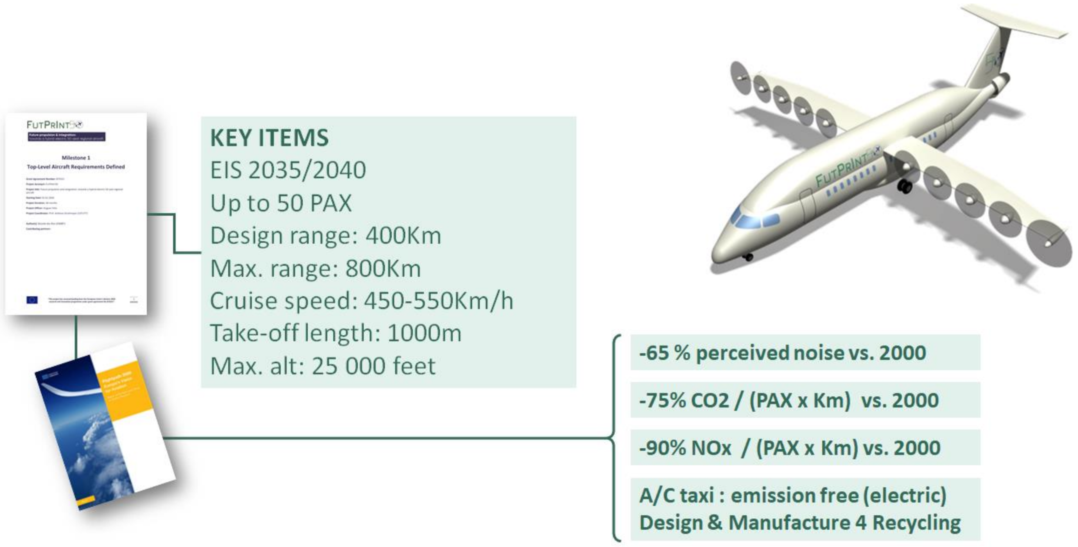

Figure 1. High level requirements for the performance (on the left) and noise and emissions (on the right) for the case study aircraft.

In the FUTPRINT 50 work breakdown structure (WBE), thermal management is included. The main expected results of the thermal management WBE are:

- to update HEA TMS state of the art;
- to identify and evaluate the HEA TMS architectures, improving trade-offs analysis and results at design stage;
- to develop new and improved models of TMS for simulation;
- to perform models integration (i.e., aircraft performance, propulsion, thermal management, etc.);
- to produce a roadmap for HEA TMS;
- to analyze current regulations/certification impacts on TMS.

2. Thermal management definition

Thermal Management can be defined as the ability to manage heat transfer between heat sources and heat sinks to control the temperature of aircraft subsystems/components in order to achieve comfort, safety and efficiency.

Thermal Management Systems (TMS) provide thermal management of aircraft systems and spaces (i.e. electronic equipment, cabin compartments, ice protection systems, etc.). Generally speaking, TMS transfer heat from one aircraft element (heat source) to another (heat sink), as shown in Figure 2. This may be achieved for instance by means of the circulation of thermal fluids that get in thermal contact with the heat sources and heat sinks. TMS architectures may comprise fluids in single phase (i.e. brines) or phase change (i.e., refrigerants, water, others) and a combination of cooling technologies such as liquid cooling systems, vapor cycle systems, heat pipes, air cooling systems, cryogenic cooling systems, etc.

Figure 2. The role of TMS in aircraft.

3. HEA thermal management challenges

Although there is a lot of research and technology development aiming at increasing the efficiency of the new electric/electronic equipment such as batteries, converters/inverters, controllers, motors, etc., what happens is that, as the power required to feed these equipment (that ultimately generate thrust to move the aircraft) is increasingly high (1 MW order of magnitude), unusual very high heat dissipation will result. These definitively "much higher than conventional" power train heat loads, both in steady state or transient (peak) conditions, have to be managed by the TMS. Consequently, higher impacts on aircraft drag (due to ram air inlets and outlets required to cool the heat exchangers for instance), weight, power consumption and costs of Electric and HEA TMS are expected. In order to make the aircraft design feasible, it is paramount to research innovative TMS architectures that decrease these aircraft level impacts.

Other relevant aspects of TMS are safety, certification and operational and maintenance issues. Regarding safety, one of the main challenges is to contain a battery thermal runaway. Essentially, once this event is started it cannot be ceased, so as a result large amounts of heat and smoke will be generated. Hence, the TMS design shall predict requirements to decrease the aircraft level impacts of a battery thermal runaway. The certification of future batteries must be better discussed between OEMs and authorities, in a way that the Equivalent Level of Safety is achieved when compared to a conventional aircraft. In that sense, considerations of systems and TMS failure modes, redundancy, MTBF (Mean Time Between Failures) and others must be performed. Regarding operations, it is mandatory to consider the reliability and maintainability of the TMS, GSE (Ground Support Equipment), spare parts and operational limitations.

The increase of electronic equipment content in aircraft design over the years is remarkable. Also, electronic equipment has been evolving to miniaturization and increased power consumption (and dissipation) designs, which lead to an increase in the heat dissipated by area (and volume). Therefore, the miniaturization of electronics increases the power density (W/kg) and heat dissipation density (W/m2, W/m3, W/kg) of equipment imposing a challenge to the TMS. Also, electronic equipment is usually installed in electronic compartments or bays which become high condensed electronics zones.

According to these characteristics of Electric and HEA, TMS may need non-conventional solutions which are described in the following chapter. These solutions are expected to bring challenges and associated risks to an aircraft design, on integration, safety, reliability, maintenance, etc., especially those related to the UK-UK (unknown unknowns). These risks must be identified early in the preliminary design phase of aircraft development due to the lack or non-reliable information available in this phase (ex.: aircraft systems architecture and capacity, efficiency, costs, MTBF, etc.). Consequently, trade-studies are important to understand the impacts of each solution at aircraft level.

4. Overview of technologies for heat transfer

4.1. Liquid cooling systems
The great advantage of liquid cooling systems is the greater capacity for transporting heat when compared to air or gases. This is due to the higher thermal capacity (mass flow multiplied by the specific heat) of the liquid, which can cool higher power dissipation equipment [1]. In addition, due to the higher density of the liquid, the transport lines become smaller. On top of that, for being (for all practical purposes) incompressible, liquids require very low power to be pumped. Cooling fluids can be thermo oils, ethylene glycol water mixture (EGW), propylene glycol water mixture (PGW), Polyalphaolefin (PAO) and others. Maintenance of liquid cooling systems is important in order to avoid leaks, fluid contamination and fire potential. Liquid cooling systems can be integrated to other aircraft cooling systems such as cabin and e-bay air cooling, skin heat exchangers and heat pipes / thermosyphons. Technology Readiness Level (TRL) today is high (>7) for aviation, being used in the Boeing 787 and military applications, as examples.

4.2. Thermal accumulators (Phase Change Materials - PCMs)
Phase change materials are substances such as graphitized carbon, sodium acetate, water and others that absorb or release large amounts of heat over a defined temperature range due to the phase transition, from solid to liquid or vice versa. Using this technology, the PCMs can provide cooling and heating to batteries, motors or electronic devices, when the material reaches its specific phase change temperature. Referred to as latent heat storage materials, the PCMs are considered highly efficient thermal storage devices. Some characteristics of PCMs are: each PCM has a defined temperature range where the material changes its state or phase; PCMs have different solid and liquid phase thermophysical properties; should be chemically stable, noncorrosive, nonflammable and safe. PCMs can be integrated to other cooling systems such as air cooling, Vapor Cycle Systems, especially to absorb high heat fluxes during equipment transient (peak) conditions. TRL today is medium (4 to 6) for aviation, as the technology is evolving by means of research initiatives related to batteries cooling for electric vehicles [2].

4.3. Pumped two phase systems (e.g. Vapor Cycle Systems (VCS), evaporative cooling)
Vapor Cycle Systems (VCS) are closed loop systems that circulate refrigerant fluid in pipework, which absorbs and removes heat from a device and rejects to a heat sink. The refrigerant fluid has specific properties under varying pressures and temperatures, and the most common refrigerants are R22, R134a and R410a [3],[4]. VCS have higher power consumption but can achieve low temperatures to cool electrical components in an aircraft and also provide air conditioning to the passengers and crew. VCS provide a much higher coefficient of performance than Air Cycle Systems. This technology allows a broad cooling envelope since the heat is absorbed at temperatures below ambient at the evaporators. VCS can be integrated to other cooling systems such as liquid cooling loops, air cooling, heat pipes and others. TRL today is high (>7) for aviation, being used in commercial (e.g. Embraer Phenom 100, Embraer Phenom 300) and military aircraft.

4.4. Air cooling (e.g., fans, air cycle machines, ram air)
Generally speaking, air cooling is accomplished by flowing air around/inside the equipment that dissipates heat. The nature of air flow can provide natural or forced convection. Forced convection is accomplished by fans inside equipment or compartments [5],[6],[7]. Also, air cycle systems (such as bootstrap systems) are used in order to decrease the cooling air temperature below ambient, through a compression, cooling and expansion cycle [3]. Thereinto, a high-pressure source of air (ex.: air flow bled from engine compressors, electrical blowers) are used. Ram air cooling is achieved at flight by ram air inlets, scoops and ducts that direct the external airflow to the heat exchangers. However, aircraft ground operations are supported by fans. There is limitation of using air cooling: ram air temperature is limited by the external air temperature. Air cooling can be integrated to other cooling systems such as liquid cooling loops, Vapor Cycle Systems, heat pipes and others. TRL today is high (>9) for aviation, being used in many aircrafts (Embraer 170/190 family, Embraer E2 family, Embraer Legacy, etc.).

4.5. Skin heat exchangers (e.g. fuselage heat exchangers)

The aircraft skin can act as a heat exchanger transferring heat to the ambient air. Skin Heat Exchangers (SHX) can be used mainly at flight conditions when the external air presents adequate heat transfer properties, such as low temperatures associated with high air speeds [8],[9]. SHX can be built using fuselage and/or wing panels that circulate the heat transfer fluid (liquid or air) through internal channels. The SHX can be part of a cooling system as an alternative or complement of ram air heat exchangers, decreasing significantly aircraft drag. SHX can be integrated to other cooling systems such as liquid cooling loops, air cooling, heat pipes and others. TRL today is high (>7) for aviation, already applied in commercial (e.g. A320) and military aircraft.

4.6. Absorption refrigerator
Absorption refrigerator is evaporation-absorption-regeneration system that uses a heat source to provide the energy required to drive the cooling process. The refrigerant is cooled during its absorption by the absorbent [10]. In aircraft with HEP associated heat from the gas turbine engine can be used for its operation. It is possible to use the absorption refrigerator as a pre-cooler in the TMS. Working fluid can be: Ammonia (NH3) + Water (H_2O), Lithium bromide (LiBr) or Lithium chloride (LiCl) salt + Water (H_2O). There are several benefits of absorption technology: utilization of waste heat of the gas turbine, no ozone-depleting components, the absence of massive moving parts and vibration, low cost of maintenance. But there are drawbacks that need to be overcome to increase TRL: presence of harmful components of ammonia-type machine and low energy efficiency. However, the relatively low cooling coefficient (60% to 80%) can be compensated by the absence of power consumption. TRL today is medium (4-5) for aviation, with low expectations of increasing TRL before 2030.

4.7. Joule-Thomson effect
Gas-cooling throttling process is commonly exploited in refrigeration processes such as air conditioners, heat pumps, and liquefiers. The air changes its temperature when it is forced through a valve while keeping it insulated so that no heat is exchanged with the environment. No external work is extracted from the air during the expansion. Therefore, free throttling of air leads to decrease of its pressure while keeping enthalpy constant [11]. Air throttling supplied to the heat exchangers of the aircraft Environmental Control System (ECS), which in general terms is responsible for aircraft fresh air flow, air conditioning and pressurization, to a pressure value close to overboard pressure will increase the efficiency of heat removal in the heat exchanger and increase the energy efficiency of the ECS. This effect is largely achieved at cruising altitude. The throttling due to the flow resistance in supply lines and heat exchangers is a source of losses that limits the ECS performance. TRL today is medium (4-5) for aviation, with probability of increasing TRL before 2030.

4.8. Vortex tube
The vortex tube, also known as the Ranque-Hilsch vortex tube, is a mechanical device that separates a compressed gas into hot and cold streams. Vortex tube has benefits such as absence of refrigerants, simple construction, no moving parts and thus high reliability. The use of the tube could potentially reduce the power consumption of an aircraft ECS. The drawbacks are the need to use high compressed gas to obtain low temperatures and relative low energy efficiency. However, isentropic energy conversion efficiency can be potentially increased from 50% to 80% [12], [13],[14]. TRL today is low (< 3) for aviation but with probability of increasing before 2030.

4.9. Magnetocaloric effect
Magnetocaloric effect is the ability of a magnetic material (e.g., gadolinium) to change its temperature and entropy under the influence of a magnetic field. HEA will probably be able to generate a high magnetic field [15],[16]. A magnetic refrigeration system commonly uses a rotating wheel structure that consists of a wheel containing segments with gadolinium powder. The wheel heats up when it crosses the magnetic field. This heat must be withdrawn. When gadolinium exits the magnetic field, the material is further cooled and thus cools the blower air directly or using a secondary coolant system. Magnetic refrigeration has thermodynamic efficiencies 20-30% higher than VCS refrigeration systems. Wide operation temperature range provides wide utilization. Relatively high output power in superconducting

magnets system provides high efficiency when this technology is used with superconductivity. The benefits of magnetic refrigeration are low environmental hazard, long life cycle, low noise, and vibration free design. TRL today is low (< 3) for aviation with probability of increasing before 2030.

4.10. Thermionic energy converter
Thermionic energy converter is a heat engine that generates electricity directly using heat as its source of energy and electrons as its working fluid. A thermionic wave generator produces electrical power directly from heat, which drives a thermionic emission process (Edison emissions) using no moving parts or working fluid, which minimizes entropy generation in the system. As a stand-alone system it can replace internal combustion engines (ICEs) across a range of applications, from household power through transportation. Integrated into combined heat and power (CHP) systems, it can transform power generation at a range of scales (e.g., from kW–MW). Projections from mini-prototype data indicate energy and power densities similar to gas turbines, however, without working fluids, moving parts or maintenance requirements [17]. TRL today is low (3,4) for aviation with probability of increasing before 2030.

4.11. The thermoelectric effects: Seebeck effect and Peltier effect
The thermoelectric effect is the direct conversion of temperature differences to electric voltage (EMF - Electromotive Force) and vice versa via a thermocouple. Seebeck effect is the buildup of an electric potential across a temperature gradient. The potential difference across the ends of two dissimilar series-connected conductors is proportional to the temperature difference between hot and cool terminals. Peltier effect is an energy transfer when an electric current passes through the junction of two dissimilar conductors, from one conductor to another. Peltier effect can be considered as the back-action counterpart to the Seebeck effect. The efficiency of the device that generates heat as a by-product can be increased by recovering the energy lost as heat and transforming it into electrical power. The higher the temperature difference between hot and cold sides, the greater the amount of power that will be produced [18]. An application of thermoelectric generators (TEG) on the nozzle of an aviation jet engine was studied and could contribute to improve the fuel consumption of future aircrafts [19]. TRL today is low (3,4) for aviation with probability of increasing before 2030.

4.12. Cryo-cooling systems
Cryo-cooling systems are used to maintain high temperature superconducting (HTS) components at temperature levels in the order of 70 K [20]. Cryogenic cooling systems can be designed with the use of Stirling and Gifford McMahon thermodynamic cycles, which present relatively high efficiency. Another approach to the development of cryo-systems is the use of Powerful Pulsating Pipes (Q-drive, USA). An important advantage of pulsating pipes is the almost complete absence of moving parts which allows to dramatically increase the reliability and the interval between maintenance operations. However, they are inferior compared to cryo-refrigerators based on Stirling cycles in terms of cooling power. The most promising cryo-refrigerators shall use turbochargers and turboexpanders based on the Brighton cycle. TRL today is low (1-3) for aviation.

4.13. Passive Systems (e.g. heat pipes, thermosyphons, vapor chambers)
Heat pipes, defined as devices that transfer heat by a process of evaporation and condensation of a fluid circulating within a sealed cavity [21] or tubing. The fluid circulation can be driven in a number of ways, most commonly by capillary forces in a porous wick (heat pipes), but also by gravitational forces (thermosyphon). Size and weight reductions are crucial requirements for aeronautical devices, leading to high power absorption rates per area. Heat pipes/thermosyphons/vapor chambers are devices adequate for high transfer rates (100 to 1000 times more than convective air) on small surfaces, therefore, adequate for large power density equipment. Also, they require low maintenance and no power consumption since are passive devices. Heat pipes can be integrated to other cooling systems such as liquid cooling loops, VCS evaporators, etc. Also, at flight the fuselage is submitted to low temperatures and high convective heat transfer coefficients, which make perfect conditions for transferring the heat of the heat pipes condensers [22].

5. Exploiting synergies: challenges as opportunities

As explained before, due to the amount of heat dissipation of HEA equipment, high impacts on weight, drag and power consumption of TMS/cooling systems at the aircraft level are expected. Therefore, integrated TMS approaches are important to minimize these impacts. Some strategies can be explored within the TMS design, such as thermal energy reuse, energy harvest, intelligent use of aircraft heat sinks, thermal accumulators, exergy-based analysis and optimization tools, etc. Some examples are (not exhaustive):

- Thermal energy reuse: circulation of a hot stream of fluid through a heat exchanger of an aircraft zone that needs to be heated (passenger cabin, door sill, galleys);
- Energy harvest: use of temperature gradients to generate an electrical potential through thermoelectric generators (taking advantage of temperature differences between motors, thermal engines, and fuselage);
- Intelligent use of aircraft heat sinks: circulation of a hot stream of fluid to skin heat exchangers, fuel tanks;
- Thermal accumulators: use phase change materials in order to accumulate “heat” (ex.: during high transients) or “cold” (ex.: at high altitude), and use them for cooling or heating in other flight phases; or bring thermal accumulators on board before flight;
- Perform a more integrated and optimized design (aeronautics, propulsion, electric systems, batteries, thermal management systems).

These for example can be explored by using exergy as a figure of merit at aircraft and systems levels[23]. Exergy based design, analysis and optimization tools can provide valuable information towards detecting and precisely localizing the major systems inefficiencies, i.e., the locations where entropy is mostly generated (or exergy is mostly destroyed). In this way, the systems designer is aware of the specific locations for potential improvement of the design (Figure 3).

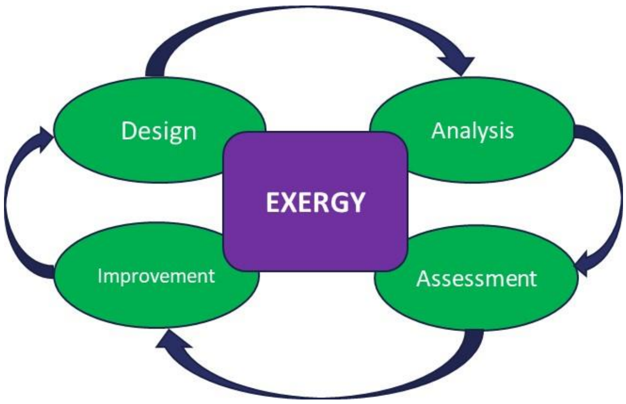

Figure 3. Interactive process using exergy as a tool for aircraft and systems analysis and optimization

6. Conclusions and way forward

TMS are essential to aircraft design since they provide comfort to passengers and crew and adequate temperature conditions for operation and enhancement of the life of electronic components. However, aircraft TMS bring high impacts on aircraft performance, safety and maintenance costs. Due to specific characteristics of HEA, an adequate thermal management approach is paramount in order to decrease impacts at the aircraft level and make the aircraft design feasible. This is aligned with the fact that an aircraft integrated design and optimization is even more relevant for future HEA.

As the way forward, FUTPRINT 50 will identify and evaluate candidate TMS architectures, exploring opportunities as exposed in this paper in order to stablish innovative TMS for HEA.

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