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FUEL CELLS AND NOVEL THERMAL MANAGEMENT ADVANCEMENTS REQUIRED FOR AVIATION.

Professor Stephen J Wright Dr.[1], Jussi Aaltonen Dr.[2],

[1]TAMPERE UNIVERSITY. FINLAND 1
[2]TAMPERE UNIVERSITY. FINLAND 2

Abstract

The paper considers the usage of proton exchange membrane fuel cells, gaseous H2 and cryogenic H2 fuels to solve the known thermal problems associated with electrical generation. Recent experimental H2 flight failures are reviewed, and a novel solution to control the electrolyte temperature operating range is proposed, utilising LH2, new additive manufactured evaporators/ heat exchangers and control software.

The need for an IRON BIRD full scale test rig is justified prior to any further ambitious flight attempts.

Keywords: fuel cell, PEM, thermal management, LH2

1. General Introduction

Decarbonization is a major challenge for aviation. The aviation sector emitted more than 900 million tons of carbon dioxide (CO2 in 2020) per year. Assuming an industry growth of 3 to 4 percent per annum (p.a.) and an efficiency improvement of 2 percent p.a., emissions would more than double by 2050 [1]. In the same time period, the Air Transport Action Group (ATAG) committed to 50 percent CO2 emission reduction (compared to 2005) and the European Union (EU) set with the Green Deal a target to become carbon neutral. Beyond CO2, aircraft impact the climate through emissions of nitrogen oxides (NOx), soot, and water vapor, which create contrails and cirrus clouds. Therefore, the “full” contribution to global warming is significantly higher than just CO2 emissions alone.

The Clean Skies for Tomorrow report, in collaboration with McKinsey & Company (11-2020)[2] assesses comprehensive and very targeted the potential of hydrogen (H2) propulsion to reduce aviation’s climate impact. It projects the technological development of H2 combustion and fuel cell powered propulsion, evaluates their technical and economic feasibility, compares them to synfuel and considers implications on aircraft design, airport infrastructure, and fuel supply chains. The conclusion is that hydrogen propulsion has the potential to be a major part of the future propulsion technology mix. As a disruptive innovation, it will require significant research and development, investments and accompanying regulation to ensure safe, economic H2 aircraft and infrastructure mastering climate impact.

H2 propulsion could significantly reduce climate impact. Hydrogen eliminates CO2 emissions in flight and can be produced carbon-free. Considering also non-CO2 emissions and taking into account the uncertainties of these effects, the latest estimates show that H2 combustion could reduce climate impact in flight by 50 to 75 percent and fuel-cell propulsion by 75 to 90 percent. This compares to about 30 to 60 percent for synfuels. To scale H2-powered aircraft, several technological unlocks need to happen: enhancing the overall efficiency with lighter tanks (targeting 12 kWh/kg / gravimetric index of 35%) and fuel cell systems (targeting 2 kW/kg incl. cooling), liquid hydrogen (LH2) distribution within the aircraft, turbines capable of burning hydrogen with low-NOx emissions, and the development of efficient refueling technologies enabling flow rates comparable to kerosene need to be developed. Industry experts project, that these important advancements are possible within five to ten years.

Assuming these technical developments, H2 propulsion is best suited for commuter, regional, short-range, and medium-range aircraft. For commuter and regional aircraft, fuel cell powered propulsion emerges as the most energy-efficient, climate-friendly and economic option.

Aviation and commercial flight is a known growth sector. Aviation is seem in the current context as one of the biggest transport means that consumes cheap fuels, yet produces significant quantities of gaseous and particulate emissions with little or no detriment to the operator/ airline or manufacture. With the better understanding of fossil fuel usage and emission measuring in the aviation mobility sector, governments have begun ensuring that new regulations are now forcing the necessary changes.

This paper will examine the current needs of the aviation sector, including the European Commissions future needs and requirements for the airborne transport mobility sector. The selection of hydrogen as the Commission's suggested future green fuel for powered flight has already been defined. The choice for the aircraft operators is whether to burn the hydrogen in gas turbine engines (which will produce water vapour plus other unwanted emissions), or to use fuel cells and electric motors to power these aircraft. The Clean Hydrogen Joint Undertaking considers Proton Exchange Membrane (PEM) fuel cells to be the current State of the Art technology further to their funding support in the Horizon 2020 programme.

However, PEM fuel cells are known to be approximately 50% efficient for electrical power generation, implying that the remainder of the energy is unwanted thermal heat generation. The paper will address the current technological challenges and limitations of PEM fuel cells, to better manage the thermal management challenges. The necessary work and subsequent demonstration flights will only be possible with significant levels of National or European funding, to prove and latterly mature the technology before PEM fuel cells can be deployed to commercial passenger service.

2. European Aviation Goals (and soon to be requirements) upto 2050

2.1 FlightPath 2050

Flightpath 2050 is a public document that details the European Commission's vision of goals for Aviation. At the time of writing, the paper identifies a series of aspirations, including the necessary reductions and improvements. In the coming years, the Commission will convert these "aspirations" to the legal statute, led by units such as DG CLIMA as seen with the ECS scheme.

Conventionally powered aircraft burn JetA1 Kerosene fuels, which produces significant quantities of CO2 and non-CO2 based emissions. Hydrogen as a fuel can be used as an aircraft carried energy source in conjunction with modern fuel cells, allowing for electric propulsion. The use of hydrogen in commercial aviation to solve the current environmental requirements is formally recognised by the EU Commission, Clean Fuel joint undertaking and Clean Aviation (formerly Clean Sky) joint undertakings have published the Hydrogen-powered aviation paper. Hydrogen is specifically identified as a viable replacement fuel source (for JetA1) for 'commuter, regional and short flights', by the reduction of CO2 and non-CO2 emissions. Specifically, the report identifies the combined use of green hydrogen with fuel cells as a viable solution to solve some of the environmental challenges, so aviation can be decarbonised by 2050.

The energy density differences between hydrogen and JetA1 have determined the application of hydrogen fuel to the types of aircraft. The report acknowledges that liquid state hydrogen (LH2) will be used in significant quantities as an aviation fuel, but presently the widespread use of LH2 is not popular, partly due to the distribution and handling challenges of the fuel. Furthermore, the gaseous H2 tanks are heavier than the LH2 tanks, and gaseous H2 fuel occupies twice the current volume compared to the cryogenic equivalent. However, the technical challenges for a viable hydrogen and fuel cell powered aircraft remain.

2.2 ZeroAvia accident, 29th April 2021. Near Cranfield Airport, UK.

ZeroAvia is an American start-up company that has significant surface mobility experience in the conversion of land vehicles to use with fuel cell technologies. The company has attracted significant start up investment and national funding from the UK government and operators, such as British Airways/ IAG. ZeroAvia have been the market leaders in fuel cell aviation activities up to the event in April 2021, with the promise of using their fuel cell know-how with airframe manufacturers to make a working demonstrator. The ZeroAvia aircraft at the time, had the worlds' leading demonstrator, being a Piper Malibu PA46-350P aircraft. The experimental aircraft was put onto the British aircraft register (Fig. 1), and contained the newest state of the art PEM fuel cell, with the modified 100kW unit supplied by PowerCell (Sweden). Powercell and other consortium members have the leading PEM fuel cell technology ‘spin out’ providers, further to the various Horizon 2020 funded projects that have been awarded to this group.

On 29th April 2021, the modified Piper PA46-350P experimental aircraft, with registration G-HYZA was undertaking experimental test flights at and very near to Cranfield Airport.

Figure 1: ZeroAvia modified Piper PA46-350P at Cranfield Airport (ZeroAvia.com)

As part of the flight test on that day, inflight, the onboard batteries were switched “OFF” so that the electric propulsion could power by the fuel cell. At this time the switch selection was made, electrical power was then lost, resulting in the immediate loss of propulsion. The pilot performed a forced landing (which is believed to be very close to the airfield perimeter).

The aircraft was severely damaged during the landing (Fig. 2), but fortunately no injuries to the crew on board were reported. The UK Air Accident Investigation Branch1 have confirmed some of the above events as per their database, and the full report is likely to be published in mid-2022.

Figure 2: ZeroAvia crashed Piper PA46 aircraft very close to Cranfield Airport (Photo: Cranfield Airport Fire Rescue)

3. Fuel Cells and thermal generation

3.1 Proton Exchange Membrane fuel cells

Recent research revealed that one of the most pressing problems with application of fuel cells is the thermal management. The waste heat of a fuel cell is less in absolute figures due to its higher efficiency, but the share of the exhaust gas, rejecting a lot of waste heat of internal combustion engines, is virtually zero. That's why the waste heat, that needs to be dissipated by an actual cooling system, is higher [3]. In addition, the operating temperature of fuel cell ranges between 60 to 80 °C only [4]. It becomes immediately clear, that the heat dissipation with fuel cell propulsion is a challenging task.

Surface transportation (i.e., buses, trains, cars etc.) that employs hydrogen with fuel cells manages the thermal performance challenges with the inclusion of large external fluid based cooling circuits with forced convection heat exchangers (e.g. with extended surfaces as the results of earlier projects indicate, that the radiator of a fuel cell powered HD trucks must be almost twice as large, compared to a conventional diesel truck, to reject all the waste heat), heat pumps or heat sinks. Furthermore, if the fuel cell units exceed a given thermal threshold, the units can be allowed to “fail” to cool-down, the vehicle park before returning recommissioning the power train to serviceable operation. Whilst hydrogen powered fuel cells are a well-known technology that have been applied to surface transport, the application to aviation has proved very problematic to date. This is because the ‘key components’ have not fully matured at this time: e.g., current PEM fuel cells have a temperature sensitive operating range (according to the fuel cell Original Equipment Manufacturers). If the fuel cell, power electronics and motors are allowed to become excessively hot, this thermal energy has a significant negative effect on the fuel cell electrolyte operation. If the electrolyte exceeds a threshold, not only is the voltage affected, but more worryingly the current flow degrades. Commercial aircraft are highly mass limited, constrained by internal volumes and the use of large extended surfaces in the airstream flow has negative consequences for the aircraft aerodynamic performance (conventional aircraft heat exchangers).

For aircraft operations, excessive thermal energy powertrain and fuel cell unit that are not correctly managed would result in the loss of propulsion, leading to an unexpected forced landing and crash/ destruction of the experimental demonstrator. This loss of power using the current technology is totally unacceptable in terms of flight safety, and explains why aviation has been very slow to develop the technology to date, compared to surface transportation. The necessary future work will differ significantly to other fuel cell research activities. The above loss of power and crash of an aircraft powered with a current state of the art fuel cell, demonstrates that retrofitting an existing airframe and trying to use “drop in COTS” technology is not the solution [4].

For example, the current SOA fuel cell (Powercell Sweden) that has a given OEM defined power output of 120 kW, also has a thermal output of 80 kW upwards under continuous load. When these fuel cells are stacked to produce a much greater power output necessary for a larger twin engine aircraft, the heat load increases likewise! To make matters more complex, current production aircraft use electrical power generated from the fossil fuel engine to power the instruments, the communication systems, lighting, heated critical probes etc., and these systems need to also be powered by the fuel cells inflight. This demonstrates the limitation of the fuel cell technology in aircraft is centred on thermal management. By utilising a different technology to control the thermal performance challenges (i.e., a different cooling system from forced convection ambient current compact heat exchangers), a new control system can optimise the performance of the fuel cells to ensure that power is always available without detriment to the fuel cell electrolyte or other systems. The current commercially available PEM fuel cell units, are the same units that are utilised for surface transportation, and their control systems are optimised for that application. PEM fuel cells are powered by the use of high pressure gaseous hydrogen. Gaseous hydrogen is readily available from a wide number of sources due to its industrial applications in other industries. The Commission’s report foresees that the first application of H2 fuel cells to commercial aircraft will be possible by 2030 for Commuter aircraft (up to 19 passengers (PAX 19) with a 500 km range with a cruise speed of 500 km/h). This will result in a 100% reduction of CO2 from the aircraft. The commuter aircraft entry to service will then mature the technologies for applications to regional aircraft (up to 80 PAX, 1000 km range etc.) that is foreseen between 2030-2035.

3.2 Evaporation of Liquid Hydrogen (LH2) fuels

Evaporation of LH2 fuels: The challenges with LH2 fuels are the continuous evaporation of the cryogenic fuel, as latent heat of vaporisation for H2 is 461 kJ/kg. The change of state requires large quantities of energy before the fuel can be used. For example, LH2 will be stored at temperatures below 20 Kelvin (K). The optimal PEM fuel cells electrolyte cooling temperature (Powercell – MW stack) is 343 K. Delta T is 323 K, being extremely large can result in the evaporators being very large. Rocket engines are able to overcome this challenge by flowing the cryogenic LH2 gas inside the booster exhausts during the burn, and such systems are designed to only operate for approximately 120 s, unlike commercial aircraft operating for 20/30 years. If insufficient ambient heat energy is not applied to the LH2 (i.e. to the very large evaporator in the ambient airflow), the evaporator unit will fail to be effective, become too cold permit the change of state of LH2 to gaseous H2. Freezing of the unit would be very detrimental, as the thermal conductivity of accumulated ice accretions would insulate the inner surfaces of the evaporator. The net result will cut gaseous H2 flow to the desired aircraft systems, resulting in a loss of power and subsequent loss of thrust, leading to an immediate forced landing.

Abbreviations should be spelt out in full the first time they appear and their abbreviated form included in brackets immediately after. Words used in a special context should appear between single quotation marks the first time they appear.

3.3 A new required solution for aircraft

The application of cryogenic and gaseous hydrogen as fuels with the heat control of aircraft powered by fuel cells is the novel approach that the industry will be required to undertake before the foreseen deployment of technologies can occur.

The fuel cells and aircraft’s thermal management issues can become resolved with sufficient funded research. This will improve aircraft performance technologies that are compatible with the aviation climate reduction operation mitigation strategies. Furthermore, resolving these systems will immediately deliver benefits for regional aircraft flight and bridge the aviation climate neutrality gap towards 2050 with the new foreseen technologies being adopted by subsequent larger fixed wing aircraft classes. In short, the new fuel cell technologies would be aligned with the environmental CO2 reduction ambitions of FlightPath 2050, Master Plan (SESAR) and ACARE.

The thermal performance of the commuter aircraft’s PEM fuel cell, power electronics and electric motor are the current challenge, as when the aircraft systems operate under normal conditions, significant quantities of thermal energy are produced. When the cumulative effects of thermal load reach a given threshold, the PEM fuel cell is unable to produce sufficient electrical power to maintain safe forward flight. The required solution for new aircraft to this safety critical problem has a thermodynamic underpinning. A novel application for cooling these temperature sensitive aircraft modules is necessary because the use of current recirculated fluid cooling or current heat pumps will result in the aircraft being too heavy and inefficient.

It is widely accepted that cryogenic hydrogen is significantly more expensive to purchase than gaseous hydrogen: This is because the production process of LH2 involves the cooling and liquefaction of the gaseous H2, requiring the usage of significant quantities of energy in the petrochemical plant. Thus, the new cooling system takes advantage of this LH2 production process (i.e. thermodynamic change of state in the petrochemical plant assuming H2 is not from green sources), without the need for the aircraft to undergo significant penalisation for additional complex thermal management systems (e.g. fitment of large external compact heat exchangers for additional cooling or heavy heat pumps).

The European Commission funded agencies have foreseen that the new commuter (PAX 19) aircraft will be powered by hydrogen and PEM fuel cells to meet the environmental ambitions and goals of FlightPath 2050. Most of the hydrogen required for operation will be provided by gaseous H2 tanks.

The thermodynamic active cooling will involve the addition of cryogenic LH2 that will be carried in new LH2 tanks. The LH2 fuel will be evaporated in a controlled manner using additive manufactured evaporator manifolds encasing some of these components' essential components (phase transition cooling). By utilising the change of state of H2, the vaporised H2 gas will be ported to the fuel cells supply to allow for the production of power. This novel dual fuel approach will allow for an optimised safe operation of the new aircraft propulsion system. A new control system for the fuel cells are also required to permit this new dual fuel approach. The optimised control software will need to port the cooling H2 gas (from evaporated LH2), to the fuel cell, whilst throttling the gaseous H2 supply. The PEM fuel cell operation being a primary safety critical system must be prioritised, as reflected by the foreseen investigations.

Thus, the proposed cooling system mostly relies on the latent heat of cryogenic hydrogen and on conventional aviation coolers as heat sinks. However, it might be advantageous, or even necessary to use additional systems for the challenging heat dissipation. Heat pumps and heat pipes are considered as the most promising systems requiring modification (and development for aviation) applications.

3.4 Heat pumps and heat pipes and the challenging applications for aircraft

Heat pump cycles (aka refrigeration cycles) can move heat energy from a lower to a higher level by introducing work to the process. This 'reverse' heat flow gives additional freedom in any thermal management system instead of depending on spontaneous heat transfer from hot to cold. However, heat pump systems require energy to work, and current SOA units are bulky, heavy and expensive. Their usage can only gain a benefit in an overall system by effecting advantages in other places. For example, a heat pump could avoid using an additional cooler outside, thus reducing the air drag and overcompensating the heat pumps power demand.

Heat pipes are passive elements that conduct heat from a hotter to a colder location using the effect of phase transition and this far better than solid materials (up to hundred times better). They have no moving parts, are maintenance free and require no additional energy to work. The special boundary conditions and limitations of an aircraft make them a very advantageous alternative to liquid-based coolant circles. Current state of the art for heat pipe applications on aircraft are the proposed used in anti-icing systems on the wings, but at this time the concept is not available or certified for commercial fixed wing aircraft (MTOM > 5700 kg). Heat pipes could make them a large heat exchanger to the ambience, and their use could also supplement the LH2 fuel usage. Both heat pumps and heat pipes can be found extensively in non-aviation applications. However, their usage in conventional aircrafts is heavily limited. Understanding the complicated interaction with the rest of the propulsion system and the revelation of potential improvement is one of the objectives of the proposed project. These thermal management components may form a small part of a breakthrough system for aviation post significant improvements, because at present, they do not fit the aircraft philosophy or physical requirements.

3.5 Additive Manufacturing and the relevance to a proposed solution

Additive Manufacturing (AM) has already shown its potential in producing high engineering customized and complex designed parts. Especially in the COVID-19 pandemic outbreak and the disruption of supply chains, the AM was able to provide a crucial support of essential goods to the healthcare, when other conventional manufacturing factories stalled[5]. To mitigate the supply chain shortage risks, stressed by the crisis, there is a trend toward regionalization and digitalization in production. This trend will promote even more the application of AM in the production of products. The possibility of generating complex geometries (generated through topology optimization tools [6]), which are capable of enhancing part properties (e.g. thermal conductivity, fluid flows [7], lightweight, etc.) makes AM a very attractive manufacturing technology components adapted to critical boundary conditions. It has been shown by Lange2018 [8], the potential of topology optimization and manufacturing via AM of a heat sink, improving five times the weight related thermal resistance when compared to the conventional design of the component. Figure 3 (below) illustrates the example of this topology optimized example.

Another example of enhancement in the performance of components through AM design was shown for a heat exchanger, having a significant reduction in weight and volume while improving 20 % the efficiency, through creating unique shapes for tubes and fins used (which are impossible to obtain with conventional techniques).

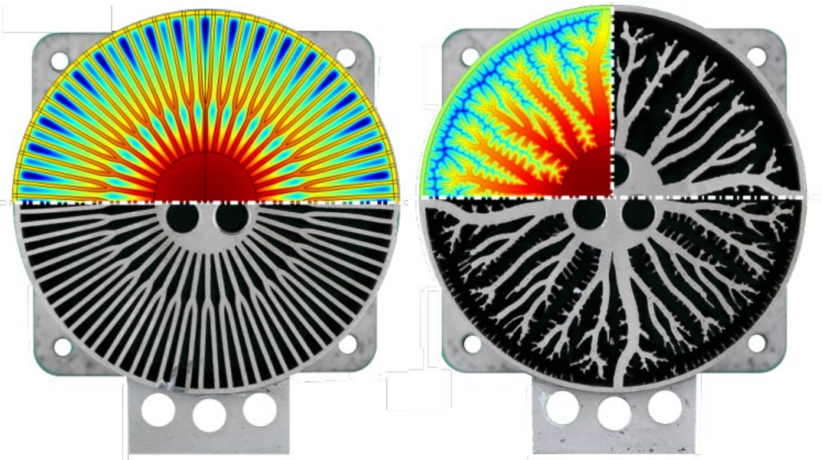

Figure 3: Example of a conventional (left) and topology optimized (right) design for a heat sink component

The following images (Fig 4) shows the conventional compact heat exchanger (left) versus the equivalent performance unit of AM applied in the heat exchanger (centre). The right image (Fig. 4) indicates the capabilities to form precise geometries that would be very difficult using normal compact heat exchanger technologies.

Thus far, the application of AM and other advanced/emerging manufacturing technologies, to produce components in the renewable energy sector have been assessed, however those studies remain at a feasibility stage of low TRL (TRL 2-3) [9],[10],[11]. Components for aircraft applications are submitted to extreme environmental conditions as pressure and temperature, which are even more critical in an aircraft powered by a PEM fuel cell [12], [13].

Therefore, in order to overcome the extreme properties requirements of the components rise also particularly interest on assessing this manufacturing route for the production of two key components in this project: Evaporator and Heat Exchanger.

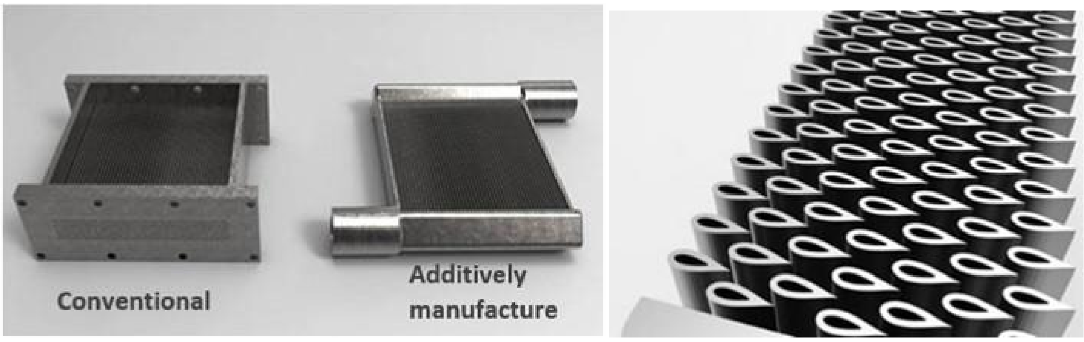

Figure 4: Conventional and AM heat exchanger design overview (left) and the unique shapes designed for the AM part (right).

4. Cooling systems and controls

4.1 Dual fuel cooling system

At the beginning of the foreseen research activities, the dual fuel cooling system concept is to be placed in a "concept phase", whereby specific approaches and implementation strategies are known and have been investigated with regard to feasibility.

A large part of the hardware components (fuel cell stacks, control units, cooling system components, etc.) are available on the market, thus use of these COTS devices is considered effective. For the general cooling system, existing cooling concepts from the automotive sector are analysed with regard to appropriate transferability. Specific components required for the innovative design of the cooling system (H2 evaporator, cooling pipe) will have to be designed and manufactured separately as part of the planned additive manufacturing process. The development of the dual fuel cooling system will be finalised with verification by series of tests on an IRON BIRD test rig. Finally, the concept for integrating the verified system into a PAX 19 aircraft is presented. In this context, a technology readiness level of 3 is targeted. The planned system will be developed up to a status where it can be tested and verified in the form of an "experimental setup in the laboratory – TRL3" (IRON BIRD test rig).

4.2 Electronic control of the cooling system

Furthermore, a new development of the system software for the control and monitoring of the fuel cell system with integrated cooling system control and monitoring is planned. In addition, an Integrated Health Management System (IHMS) is being developed to achieve a significant increase in reliability through targeted status monitoring and early fault detection and to sustainably improve the lifetime of fuel cell systems. The degree of software development is set with the completion for implementation in the control hardware of the IRON BIRD test rig, in which series of tests of the entire fuel cell system are performed. Thus, a Technology Readiness Level of 3 is required, as the system will be designed for the "experimental setup in the laboratory – TRL3" (IRON BIRD Test rig)..

5. Proposed methodology to test the viability of a new cooling system

The LH2 evaporators that are critical to the application of the active cooling for the thermally sensitive, will be optimised to ensure size/ performance and material safety. The final assemblies will be additive manufactured to reduce mass, size and ensure an optimal performance. The printed materials will be carefully selected to ensure the gaseous diatomic hydrogen does not permeate through the material, that would result from a gas leak. Modular gaseous H2 and LH2 tanks are required for the proposed PAX 19 Commuter aircraft. The new modular fuel tank designs will permit the fully developed aircraft to be refuelled on the airport apron without the new infrastructure at gate.

The validation and testing of all systems will be performed in a remote location (to mitigate risks) on an “IRON BIRD” ground installation. The use of gaseous and liquid hydrogen fuels poses a unique safety problem. The likelihood of fuel leaks are very high, so indoor bench testing of the full apparatus is discouraged. The IRON BIRD will allow the representative systems to be fitted inside a weather-tight shipping container that has various gas vents to mitigate leaks/ fire/ explosions and will incorporate misting fire / explosion suppression. The test area will need to be sterile with technicians a safe working distance from the rig. The rig will need to be positioned outside and operated at intervals throughout the year to replicate real world conditions. It is expected that the test apparatus will need to replicate the real-world range of temperatures, i.e. from stable winter conditions of minus 30 °C to the extreme summer heat of approximately plus 35 °C. This range of ambient conditions will prove the active cooling system operation, in addition to the foreseen new health monitoring and control systems.

The PAX 19 aircraft design requirements will be defined by the Original Aircraft Equipment manufacturer, that can utilise the new foreseen powertrain, fuels and fuel cells, underpinned by their current EASA certification rights and experience. The final activities of the project will be to use the predicted experimental and data, to apply these to the PAX 19 concept, and to extrapolate beyond the expected TRL 3 to a higher level.

As part of the development of the dual fuel cooling system for the target aircraft (PAX 19), the system requirements to be fulfilled are previously defined in measurable form (electrical power, cooling capacity, reliability, etc.). This task is completed by performing a requirements analysis, in which all the requirements to be considered are first listed and then prioritized according to relevance, so that an overview of content and relevance of each requirement is generated. In a next step, fluid dynamic models of the system to be designed according to the requirements are developed in order to make specific predictions regarding the system behaviour of the cooling circuit. Different variations are considered and prioritized according to effectiveness.

Subsequently, a design of the cooling system in the form of a system layout is developed based on the knowledge gained from the requirements analysis and the investigation of the system behaviour. In this context, the individual subcomponents are defined and combined to build an overall system design in which all subcomponents are taken into account and new components to be developed are defined. Based on the overall design, the cooling system will be built up in order to be tested on a test rig. Test series definition is carried out analogously to the requirements analysis in order to evaluate all measurable parameters with regard to the defined requirements. Finally, the verification of system functionality will need to be performed based on physical series of tests on an IRON BIRD test rig.

Investigations into heat pipes and heat pumps are primarily based upon numerical and theoretical work. There are a large number of possibilities to add a heat pump to a fuel cell's thermal management system. It is clearly not feasible to put them all on the test rig, and it is not even feasible to simulate them all. Thus, a first screening of variants will be done by theoretical work supported by strongly simplified calculations. Literature of comparable undertakings will support this step in the very beginning of the task. Several promising variants will need to be further considered in more detailed simulations. Commercial tools for zero- and one-dimensional simulation of fluid-,energy- and heat flow will need to be engaged. The simulation will be time-dependent in any case, since it can be assumed that fuel cell thermal management systems do not have a steady state even during cruise operations. It will be necessary to connect the heat pump model to the other project's simulation models (fuel cell, evaporator, battery, etc.) by means of a coupled simulation approach. Based on this plant simulation model a (sub) operating strategy for the heat pump system will be required to eventually gather a quantified potential of the individual variants improvement of the overall system performance. The variant that is most reasonable would then be procured and prepared to be tested on the iron bird test rig for verification and demonstration. The approach to heat pipe investigations would be somewhat different. Heat pipes do not have anything like an operating strategy (because they are passive). They have only limited interaction with other parts of the thermal system and thus, they can be considered as standalone components. The more difficult part with simulating heat pipes are the processes of evaporation, condensation, heat transfer, liquid and gaseous mass transport. Commercial 3D-CFD tools claim to be capable of these simulations.

However, it has yet to be determined whether a very detailed thermodynamic simulation is necessary at all. A more conceptual approach could be plausible, including general questions of packaging, weight and design under the challenging boundaries of aviation. However, a major effort for model development is required. Whatever tools are utilised, the required work envisages that several variants will need to be investigated in detail and the most appropriate solution will be selected, procured and prepared to be tested on the iron bird test rig for verification and demonstration. The system development would be based on the application of the following methods: Performing a requirements analysis, development of a model-based prediction of the system behaviour, definition of the subcomponents, development of the overall system layout, design of the physical system structure, performance of a functional verification, final system validation. That would cover all relevant parts and their links amongst each other to tackle the complicated interactions of the system. The simulation would be performed as time-dependent one-dimensional consideration of fluid- heat-and energy-flows. Commercial tools would be used, that will be complemented with new or proprietary sub-models where required.

6. Conclusion

The following conclusions can be drawn:

The drop in technology approach attempted by companies, and the subsequent failures (including the demonstration proof of concept aircraft crash) illustrate the complexities of the grand challenges faced by all those involved, who are attempting to incorporate fuel cell technologies for electric propulsion.

Ensuring that the PEM fuel cell electrolyte temperature remains within temperature tolerances is critical to the ability for the production of electrical power to maintain flight. If the power supply is interrupted, the aircraft will be required to perform a forced landing. The continuous supply of electrical power to the electric motors is a flight safety critical function – with instrumentation and radio communication needs after that.

The current usage of large extended compact heat exchangers for fuel cell electrolyte cooling is not a viable option for commercial passenger aircraft, that are capable of carrying upto 19 passengers and beyond. This is attributed to the high speeds of the aircraft and the factors that would affect the drag and other flow related performances. Likewise, the usage of commercial off the shelf heat pumps or heat pipes likewise is not deemed as effective, due to the size, weight and volume restrictions that aircraft uniquely pose.

The novel cooling system could be demonstrated from basic thermodynamic principles, namely the latent heat of vaporisation (liquid to gas) of a cryogenic fluid such as LH2. However, the evaporators and heat exchangers will require considerable theoretical modelling and manufacture using additive manufacturing technologies, necessary to overcome the volume and mass challenges.

A dual fuel approach (i.e. gaseous H2 fuel and LH2) will be required to ensure maximum levels of safety and redundancy. The high pressure gaseous H2 fuel would ensure the continuous supply of propulsion H2 fuel to the fuel cell at all times. The LH2 evaporator and heat exchangers would solve the current thermal management heat issues and ensure the optimal control of the PEM electrolyte, and vaporised H2 can be consumed by the fuel cell as fuel.

Additional testing of state of the art heat pumps and passive heat pipes can complement the cryogenic cooling system, yet the phase change thermodynamic processes will permit the electrolyte to be maintained at the optimal levels.

A proposed IRON BIRD test rig that can operate in similar environmental conditions to an aircraft inflight is necessary, to prove the safe operation of all the systems before demonstration flights occur. Due to the unique risks of H2, remote locations for these activities will be required.

Assuming that the above testing processes are carried out with the satisfactory results, only then could the fitment of this new technology to an existing aircraft be carried out, prior to experimental proving flights. Failure to do so, will result in the expected generation of significant levels of thermal energy, boiling the PEM electrolyte and the immediate loss of power and potentially the aircraft.

7. Contact Author Email Address

Electronic mail to: stephen.wright@tuni.fi

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