ADVANCED THERMAL MANAGEMENT IN AVIATION: SOLUTIONS FOR MEGAWATT-SCALE SYSTEMS

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Summary

One of the main challenges for fuel cell propulsion, aside from hydrogen storage and the fuel cells themselves, is thermal management. Fuel cells dissipate around 50% of the energy as heat, necessitating cooling systems up to a megawatt range for a 100-passenger aircraft. While such cooling systems are widely used in ground applications, including pumps, fans, heat exchangers, sensors, pipes, reservoirs, filters and valves, there are currently no airborne cooling systems in the megawatt range available.

A lightweight and reliable system approach with two liquid cooling loops will be presented. Design approaches for key components will be discussed, including a design to achieve a 70% weight reduction for the cooling fluid pump compared to ground pumps. Additionally, the impacts of using active versus passive thermal expansion reservoirs and the design approaches for liquid-to-air heat exchangers as well as thermal control valves will be explored.

1. INTRODUCTION

The aviation industry is undergoing a transformation toward sustainable propulsion technologies. Hydrogen fuel cells, with their potential for zero-emission operation, are central to this evolution. Yet, their successful deployment in aircraft hinges on the ability to manage heat effectively. Unlike conventional engines, fuel cells operate within narrow temperature windows, and their efficiency is highly sensitive to thermal fluctuations. Moreover, the power densities required for commercial aviation on the order of megawatts demand thermal systems that are not only efficient but also lightweight, compact, and robust under dynamic flight conditions.

To address these challenges, Airbus and Diehl Aviation have developed a scalable thermal management system tailored for a 1 MW hydrogen propulsion demonstrator. Designed for short-range aircraft carrying up to 100 passengers over 1,000 nautical miles, the system integrates advanced cooling technologies, smart control mechanisms, and modular components to ensure optimal performance and safety.

This paper presents the System Architecture of the Thermal Management System, followed by the key components Coolant Pump, Heat Exchangers, Reservoirs for compensation of thermal expansion and the Thermal Control Valve for mixing of different coolant flows. The paper concludes with an Outlook on planned testing activities.

2. SYSTEM ARCHITECTURE

The Thermal Management System is based on a dual-loop cooling architecture (figure 1). The first loop is dedicated to fuel cell thermal regulation, operating at optimal temperatures and incorporating precise mixing of cold and warm coolant streams. Each fuel cell channel is equipped with its own pump, enabling fine-grained control and redundancy. An active pressure reservoir minimizes system volume while maintaining stable pressure across varying thermal loads.

The second loop serves auxiliary components such as motor controllers, converters, and actuators. Operating at lower temperatures below 70°C, this loop also preconditions hydrogen via integrated hydrogen heat exchangers, enhancing the overall thermal efficiency.

Waste heat from both loops is rejected to ambient air through a modular array of liquid to air heat exchangers, allowing scalability and adaptability to different aircraft configurations.

The system is designed to operate across a wide temperature range from −55 °C to +100 °C and supports coolant flow rates between 2 and 8 l/s per pump with pressure increases of up to 10 bar. These environmental boundary conditions ensure compatibility with high-performance fuel cell stacks and electrical systems.

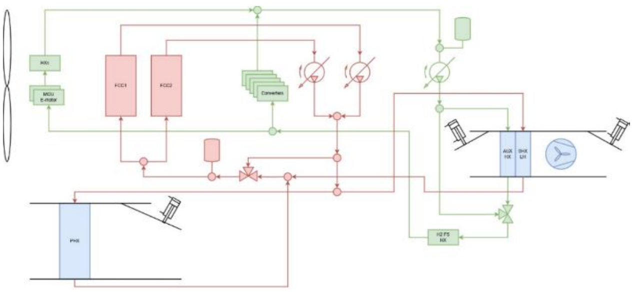

Figure 1: System Architecture

Safety is a core design driver for the architecture and individual components. This includes electrically commanded shut-off valves and passive check valves on architecture level to isolate key zones, e.g fuel cell encapsulation, in the event of a leak or emergency shutdown to minimize potential coolant leakages as well as specific requirements, e.g. with respect to electrical safety of motor controllers in each equipment.

Another critical aspect of the design is system integration with specific technical directives for pipe routing, material selection, and component placement to address constraints related to weight, volume, and safety. The design prioritizes the reduction of pipe diameters to minimize overall system weight, including the coolant itself. However, this optimization increases pressure loss, which in turn necessitates higher coolant pump performance. To manage these trade-offs, the system design employs a series of iterative studies to balance efficiency, weight, and component longevity.

From this system level individual requirements for the different components are derived which are used for the detailed design described in the following sections.

3. PUMP

A key enabler of the system’s performance is the aviation-grade pump (figure 2). Unlike conventional industrial pumps in this power class, which can weigh over 120 kg, the Diehl pump is engineered for airborne use, weighing just 30 kg. It features a centrifugal hydraulic stage with a highly efficient synchronous motor, capable of variable-speed operation and integrated overheat protection. The pump is liquid-cooled and powered via HVDC, with smart electronics that interface directly with aircraft systems. Safety features include EMI shielding, internal contactors for fast shutdown, and built-in test equipment for diagnostics.

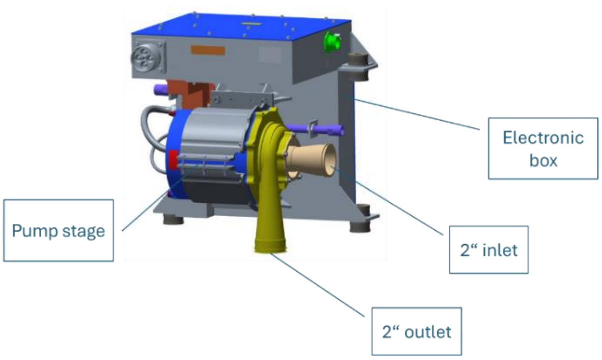

Figure 2: Pump Design

In figure 3 the pump performance diagram is shown, demonstrating the large flow and pressure working range. The diagram illustrates the pump’s power consumption for different flow rates at different pump speeds.

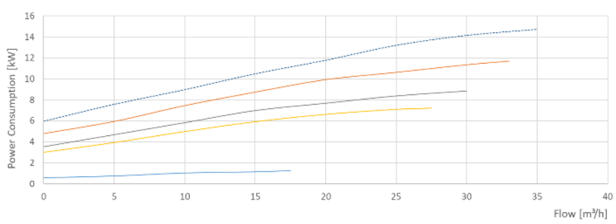

Figure 3: Pump Performance Diagram

4. HEAT EXCHANGERS

Heat exchangers are another cornerstone of the system. The primary heat exchanger, located in the ram air channel, employs a cross-counterflow design to maximize heat transfer on a minimal surface area. It is lightweight and structurally robust, capable of withstanding propeller-induced vibrations. A tandem configuration of auxiliary and secondary heat exchangers (figure 4) ensures efficient temperature stratification, with the front unit maintaining lower temperatures and the rear unit handling the higher temperatures and thermal loads from the fuel cell loop.

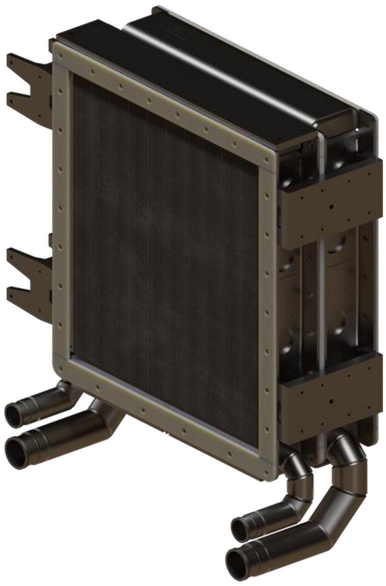

Figure 4: Auxiliary and Secondary Heat Exchanger

In figure 5 the heat transfer performance test of the heat exchanger is shown demonstrating the efficient transfer.

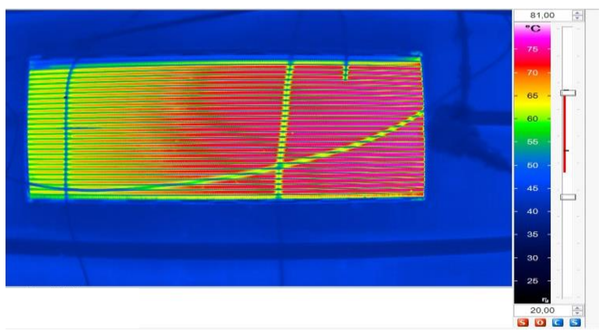

Figure 5: Heat Exchanger heat transfer performance test

5. RESERVOIR

The reservoir compensates the cooling fluid expansion over the temperature range to maintain the operating pressure range. In principle the reservoir design reflects a balance between simplicity and performance. In a passive reservoir (figure 6, left) the expanding volume is compensated by compressing a gas, optionally with an additional separation membrane.

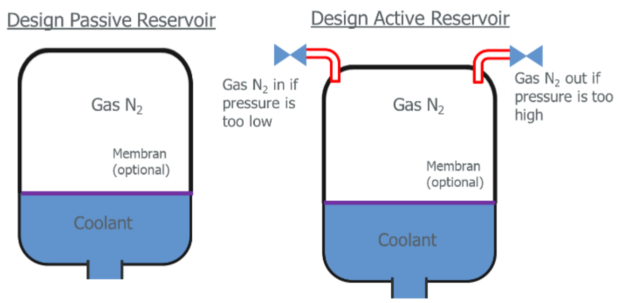

Figure 6: Design passive and active reservoir

A passive reservoir for the fuel cell loop would hold over 125 liters for the operation within a pressure range of 1.5 to 3 bar in the temperature range of −55 °C to +100 °C with a coolant volume of over 200 liters (figure 7). This would be too large and heavy for an airborne application.

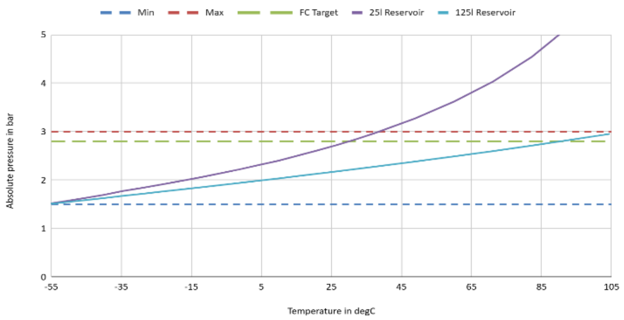

Figure 7: Pressure-Temperature Diagram for Passive Reservoir

In an active reservoir the pressure is actively controlled by gas in- and outlets (figure 6 right and figure 8). With this approach the volume of the fuel cell reservoir can be reduced from 125 liters to 25 liters by adding gas in- and outlet valves and a pressure sensor to the reservoir. This design meets Thermal Management System requirements while significantly lowering system mass and volume.

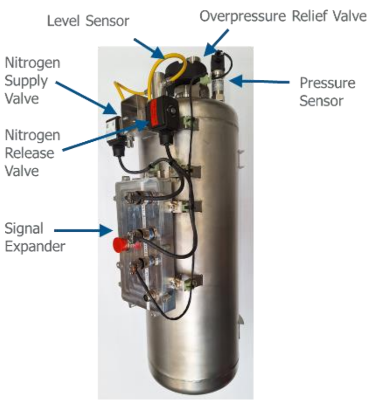

Figure 8: Active Reservoir

In the Auxiliary Loop the situation is different, the pressure range is enlarged to 1.3 to 3 bar and the temperature range is reduced to −55 °C to +80 °C with a coolant volume of around 100 liters. This results in a passive reservoir of around 30 liters not justifying the additional complexity of the active reservoir.

6. THERMAL CONTROL VALVE

Temperature control is achieved with a precision thermal valve that mixes hot and cold coolant streams. The ball valve is designed that based on simulations a rotation angle adjustment of 3 degrees, results in a shift of the outlet temperature by approximately 1 °C (figure 9). Its fast response time and low-pressure loss (<0.4 bar) make it ideal for maintaining fuel cell operating conditions and to run the fuel cell at high efficiency during rapid changes of flight conditions or during different mission profiles.

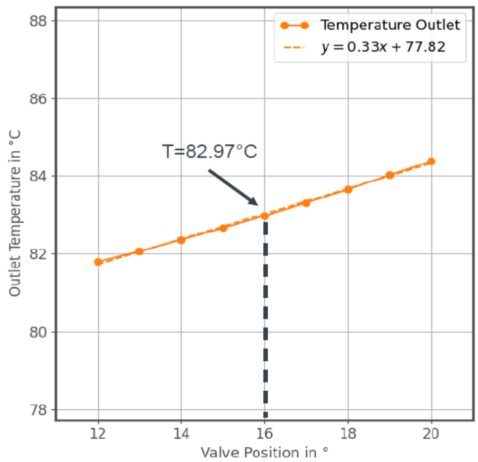

Figure 9: Temperature Control of the Thermal Control Valve

7. OUTLOOK

In the next project phase, the presented equipment will be thoroughly tested against the requirements. The functional design will first be verified on equipment level and later on system scale as part of the FAME ground demonstrator. In addition, critical aviation qualification tests, such as electromagnetic compatibility (EMC), temperature variation and vibration will be performed with the presented equipment paving the path for a future airborne application.

8. CONCLUSION

The Thermal Management System demonstrator marks a pivotal step toward the realization of hydrogen-powered flight. By combining scalable cooling capacity, lightweight components, and robust control mechanisms, the system addresses key barriers to fuel cell integration in aviation. Its successful validation paves the way for next-generation aircraft that are not only efficient and reliable but also environmentally sustainable.

9. ACKNOWLEGMENT

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101140559. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation. Neither the European Union nor Clean Aviation can be held responsible for them.

Figure 10: Project Funding