

Using the DLR Thermofluid Stream Library for Thermal Management of Fuel Cell Systems in Aviation

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Abstract

For more environmental friendly aircraft, different propulsion systems are considered. Either fuel cell or fully electrically driven aircraft come along with challenging heat dissipation tasks. An intelligent thermal management system is essential to prevent failures and to ensure a reliable operation of the propulsion system. The exploration space for appropriate cooling systems seems endless, hence it is vital to rely on robust modeling libraries that enable a quick design and simulation of different architectures. The open source DLR Thermofluid Stream Library (TFS) forms such a basis and proved to be expedient in that sense. This paper gives an overview of a complete fuel cell system for future aircraft that covers the most essential subsystems and is modeled solely of components contained in the TFS. The focus is on different cooling systems and methods that can be quickly investigated in the context of the overall fuel cell system throughout an entire flight mission.

Keywords: Thermofluids, thermal management, robust modeling, fuel cell systems, open source software, prototypical control

1 Introduction

In order to reduce greenhouse emissions, intensive research is currently being carried out into new types of propulsion systems for aircraft. Using fuel cells to provide the required energy to power the propellers of an aircraft is one concept among others. Different architectures were investigated for example in the DLR internal EXACT project (*EXACT – Conceptual study for future climate-neutral flight* n.d.) and one possible design of a liquid hydrogen (LH₂) driven fuel cell aircraft is shown in Figure 1.

The idea is to integrate the fuel cell directly into the nacelle that is mounted on the wing, with multiple nacelles forming the total propulsion system of the aircraft. A sketch of a possible nacelle-integrated setup is shown in Figure 2. As the total required power is in the order of several Megawatts and with an efficiency of modern proton exchange membrane (PEM) fuel cell stacks of approximately 50%, a huge amount of heat is generated during the process. PEM fuel cell stacks typically operate between 60 °C and 90 °C. Low grade heat in such tempera-



Figure 1. LH₂ driven Fuel Cell Aircraft from EXACT project.

ture regions is challenging to remove due to the small temperature difference to the ambient in comparison to conventional combustion engines. Throughout a flight profile, the ambient temperature can vary from 40 °C at take-off to –50 °C in cruise conditions. This variation results in a substantial increase in the temperature difference between the fuel cell and the ambient air during a single mission. In order to dissipate the heat at take-off conditions, a large, heavy heat exchanger is required. Contrary, in cruise conditions significantly smaller components would be sufficient and most of the cooling system becomes unnecessary dead weight. Therefore it is beneficial to investigate advanced and novel cooling system concepts to minimize the impact of the cooling system on fuel consumption.

In addition to the fuel cell, there are other heat sources that need to be cooled like the motor and the converter of the power train or a battery. Additionally to cooling, the fuel cell has to be supplied with a sufficient oxygen and hydrogen flow. For optimal operation, the conditions of the supply flows have to match very precise requirements regarding temperature, pressure and humidity. All the mentioned subsystems need some sort of cooling that can be realized in many different ways. The mechanisms vary from simple liquid cooling to direct evaporation in the fuel cell and vapor-compression systems. A dedicated number of ram air channels is used as the main heat sink for each cooling task. Using alternative heat sinks like the LH₂ supply lines are also under consideration to be included in the overall thermal management.

This paper will give an overview on the capabilities of the Thermofluid Stream Library (TFS) (Zimmer, Weber,

and Meißner 2021) to model the main domains of a fuel cell system and its subsystems. The strength of the library is the avoidance of large non-linear equation systems when setting up thermal networks, due to a new approach on modeling thermofluid streams. It enables an easy set up and initialization of the system models and leads to high robustness and performance. The library and its modeling approach will not be further presented in this paper, detailed explanations can be found in (Zimmer, Bender, and Pollok 2018) and (Zimmer 2019). After introducing the overall system model, the focus will be on different cooling systems and methods. Common interfaces enable a quick and easy configuration of different cooling systems that can be tested in a mission simulation in the environment of the overall system. Nevertheless, the prototypical control design that is necessary to guide the systems through the fast changing operating points of a flight mission are only briefly discussed in this paper. As a conclusion, results of an exemplary flight mission will be compared and discussed.

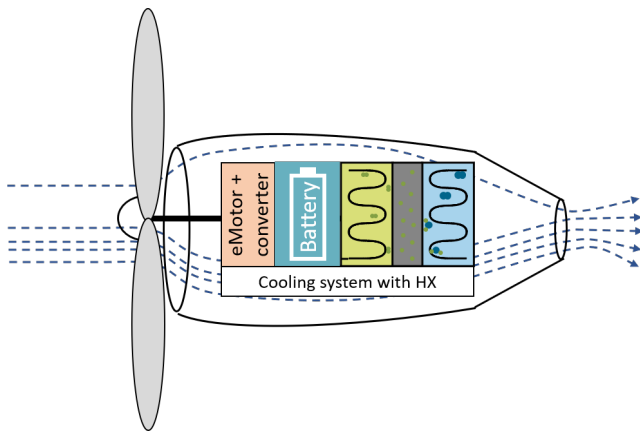


Figure 2. Sketch of a nacelle-integrated fuel cell propulsion system consisting of a propeller, electric motor, converter, battery, fuel cell stack and cooling system.

2 Fuel Cell System

The top level of the overall fuel cell system and its subsystems is shown in Figure 3. It consists of a fuel cell model, air and LH2 supply, components of the power electronics and the cooling system. The ambient and boundary conditions are provided by an environmental bus from a flight mission block. As this paper mainly focuses on the cooling system, the other subsystems are only briefly explained in the following.

The central heat load of the system is the fuel cell. Our model contains the main reaction equations to convert chemical energy into electrical energy. The resulting heat load is calculated from an energy balance across the whole fuel cell component and is essentially determined by a fixed efficiency. The power input of the fuel cell stack is connected to a converter and a motor. Both power electronic components are efficiency-based models. This

means, that the fuel cell will always deliver the power that is requested from the shaft, taking the losses of the converter and the motor into account. In critical flight phases as take-off or overshoot with very high power demand, a battery can serve as a booster in order to relieve the fuel cell. However, in the current state of our models, the battery is not yet included.

The air supply provides the required oxygen mass flow to the fuel cell. Outside air is taken from a separate inlet and is fed through a compressor and heat exchanger to be prepared for the required conditions of the fuel cell. Optimal operating conditions of PEM fuel cells in aircraft were derived in a detailed study by (Schröder et al. 2021).

In our model, the supply air is controlled to a constant temperature near stack conditions at a pressure of 1.6 bar and a relative humidity of 75%. During a flight mission, the optimal set points may vary depending on the flight phase but for the sake of simplicity, they are initially kept constant. To control the humidity, the required amount of water is extracted from the fuel cell exhaust gas and injected into the air supply. In practice, this task would be carried out by a membrane humidifier. At the current state, a combination of idealized water extractor and injector models are used to fulfill this task. Integrating a component model of a membrane humidifier is planned in future research activities.

3 Fuel Cell Cooling System

The cooling system enables temperature control of the fuel cell and power electronics, by rejecting heat to either the LH2 supply or to the ambient air using a ram air channel. To obtain optimal fuel cell efficiency, the LH2 needs to be warmed up from its cryogenic storage temperature to approximately the same temperature of the fuel cell itself. This provides a heat sink, capable of absorbing approximately 10% of the generated heat, without causing any drag on the aircraft. The detailed modelling of LH2 as a heat sink is planned to be investigated in future research activities, however, in this paper, the focus is on using the ambient air as the only heat sink. A potential cooling system interface is shown in Figure 4. In this case the cooling loops are separated and the heat from the fuel cell is rejected to a different ram air channel than the heat from the power electronics. This enables an independent control of the heat loads and increases the total cooling capacity.

For the thermal management of fuel cell systems, many different cooling strategies can be applied. A detailed review of different cooling methods for PEM fuel cells was carried out by (Chen et al. 2021). In the following, a selected variety of different cooling concepts is presented. For each system architecture, ambient air is utilized as heat sink. To this end, the outside air is captured and guided through the system by a dedicated number of ram air channels. Different kinds of heat exchangers inside the channels reject the heat into the ram air flow. By leveraging the high robustness and easy usability of the TFS,

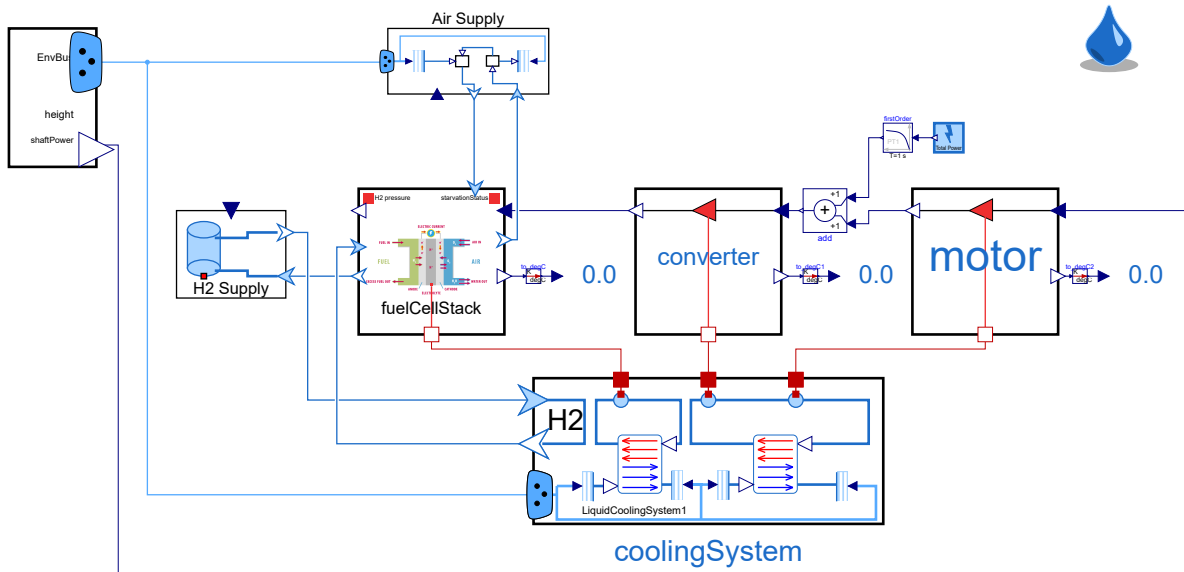


Figure 3. Modelica model of the overall fuel cell system.

different cooling systems can be rapidly set up, compared and optimized. For all concepts, the main objective is to maintain a constant fuel cell operating temperature of 80 °C.

3.1 Ram air channel

For all cooling systems, the common ram air channel design shown in Figure 5 is used. In this system, the valve represents the ram air door at the intake with variable opening, which is mainly used in cruise to control the amount of airflow through the channel. In ground operations, the door is fully open and sufficient airflow is generated by the ram air fan. Depending on the flight phase, the control split feeds the input signal of the controller to either the valve or the fan to ensure sufficient cooling airflow. The geometry of the ram air channel is modeled by the dynamic pressure boundaries to convert the air velocity into dynamic pressure.

As shown in Figure 4, distinct ram air cooling systems are used for the fuel cell and the power electronics. For the sake of simplicity, the following description of cooling systems is tailored specifically to the fuel cell, while a liquid cooling system is used for the power electronics in each case.

3.2 Liquid Cooling

The liquid cooling system shown in Figure 6 utilizes a single-phase medium, which directly transfers heat between the heat source and the heat exchanger within the ram air channel. This means that the sensible heat of the coolant is used and the heat transfer results in a temperature increase of the coolant. Typically, a mixture of deionized water and propylene or ethylene glycol is used as a coolant to lower the freezing point. This type of cooling system is commonly used in the automotive industry for fuel cell electric vehicles.

In this system, the pump is controlled in a way to maintain a constant temperature difference of the coolant across the fuel cell, while the ram air channel controller directly controls the temperature of the fuel cell itself. While being simple in the design, this system possesses a fundamental limitation, due to the relatively small temperature difference between the coolant and the ambient air at take-off conditions. This requires a large heat exchanger in the ram air channel, inducing significant drag and weight on aircraft level, which is carried through the entire flight profile.

3.3 Evaporative Cooling

In order to improve the efficiency of the heat exchange between the fuel cell, coolant and ram air, a phase-changing coolant like methanol can be used. For two-phase coolants and refrigerants, we use the media models from TILMedia Suite (*TILMedia Suite - Software package for calculating the properties of thermophysical substances* n.d.) developed by TLK Thermo GmbH. An internal wrapper was implemented to match the interfaces of the TFS to enable the usage of the external media models.

By evaporating methanol inside the fuel cell and by condensing it inside the heat exchanger in the ram air channel (condenser), heat exchanger efficiency can be improved, since the much larger latent heat instead of the sensible heat is utilized and the heat exchange occurs at a constant temperature. The most simple version of a system following this concept can be seen in Figure 7, where the methanol is simply circulated by a pump. In order to prevent damages, it is necessary to ensure that the methanol reaches the pump in a liquid, subcooled state. If the coolant could not completely be condensed in the ram air channel, the phase separator after the heat exchanger serves as a buffer element and only feeds liquid methanol to the pump. The points 1 and 2 correspond to the operat-

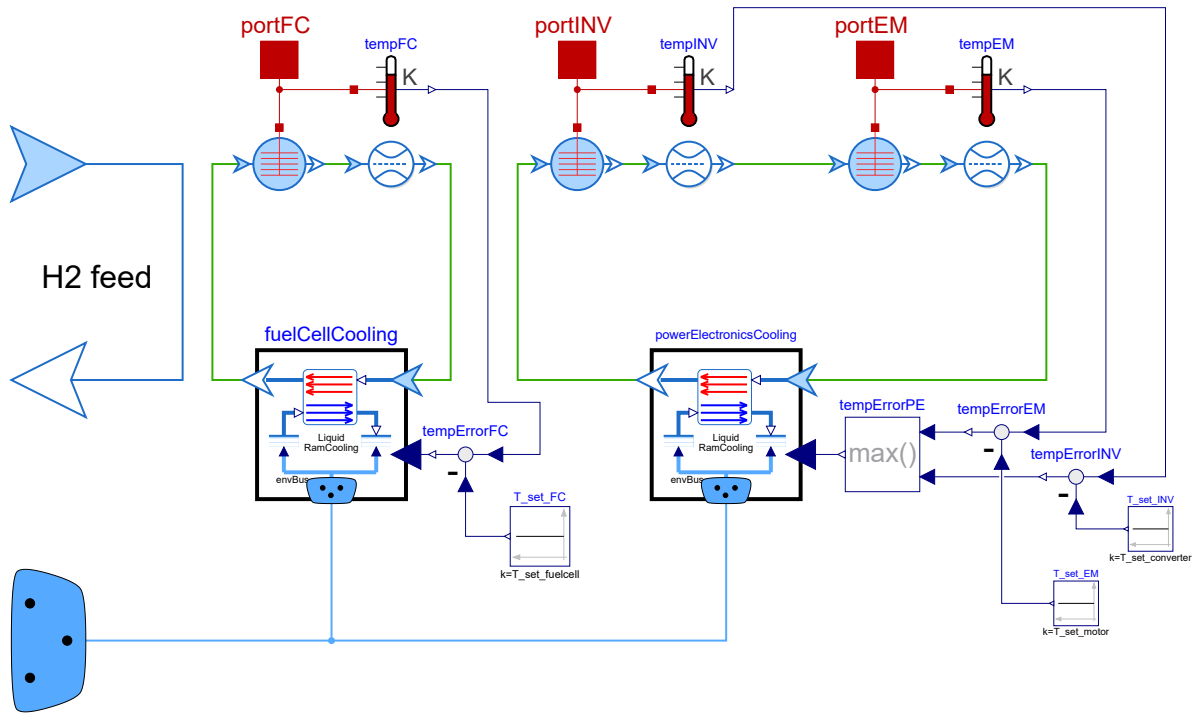


Figure 4. Modelica model of the overall cooling system. This model contains a dedicated ram air channel for the fuel cell, as well as a separate one for the remaining power electronics. No heat rejection to hydrogen is considered in this case.

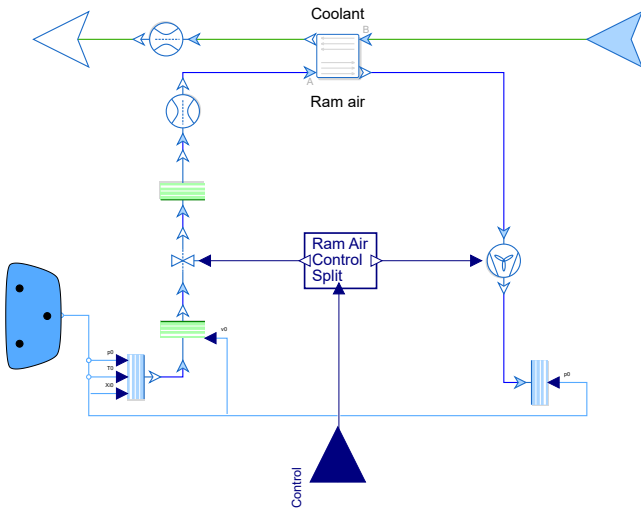


Figure 5. Modelica model of the ram air channel, consisting of a source, a sink, and a dynamic pressure flow section around the valve.

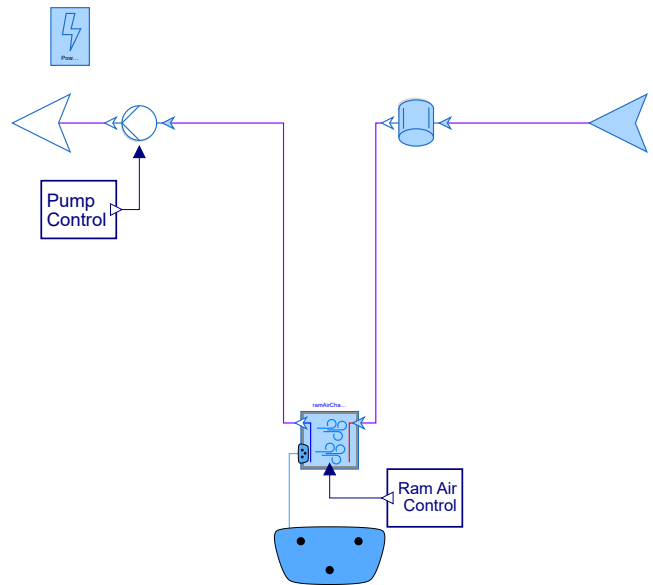


Figure 6. Modelica model of the liquid cooling system.

ing points in the generic pressure-enthalpy diagram shown in Figure 8. The vapor fraction at the outlet of the fuel cell (point 2) is controlled to a constant value by controlling the speed of the methanol pump. The limited vapor fraction prevents too much evaporation of the coolant in the fuel cell and hence avoids instabilities due to a drastic increase in volume during the evaporation process. The fuel cell temperature target is reached by controlling the ram air channel airflow. Since the evaporation at the fuel cell occurs at a constant temperature, this effectively results in

regulating the pressure level p_{low} to ensure sufficient heat transfer from the fuel cell to the coolant.

An enhanced version of this system can be seen in Figure 9, where the liquid and gaseous methanol are separated to ensure that only the gaseous methanol flows through the condenser in the ram air channel. This means that not the entire coolant flow has to flow through the heat exchanger and hence it can be reduced in size and weight.

This bypass system results in the operating points 1, 2 and 3 in Figure 8. The vapor fraction at the fuel cell outlet

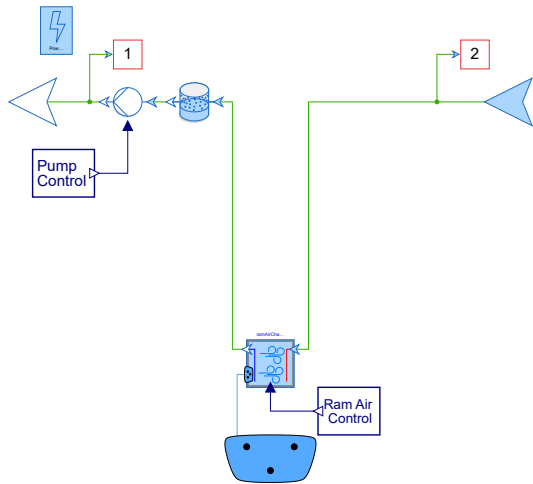


Figure 7. Modelica model of the simple methanol loop.

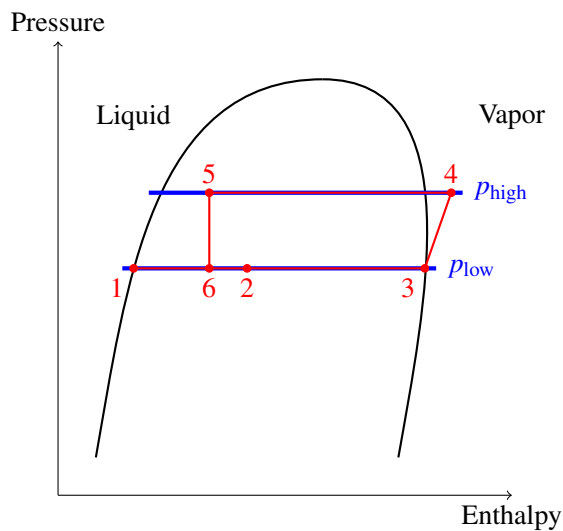


Figure 8. Generic pressure-enthalpy diagram applying to methanol cycles.

is still controlled to a constant value at point 2, while the ram air channel controller ensures that enough airflow is supplied to fully condense the methanol, ensuring a liquid state at the inlet of the secondary pump. The second pump controls the temperature of the fuel cell by adjusting the pressure level p_{low} .

A further improvement of the cooling efficiency can potentially be achieved by increasing the condenser inlet temperature. To this end, the previous variant is expanded by a compressor that lifts the pressure and temperature before it enters the condenser, as shown in Figure 10. In take-off conditions, this can more than double the temperature difference between the coolant and ambient air. After the heat exchanger, the methanol is subsequently expanded to the desired operating pressure by an appropriate flow resistance. A direct routing to the pump would require a high level of subcooling in the condenser

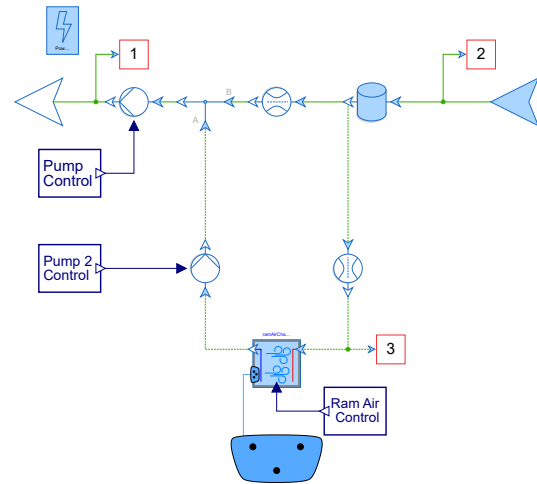


Figure 9. Methanol cooling cycle, including a separator to divide the liquid and gaseous phase.

to ensure that the methanol still enters the pump in a liquid state after expansion. This would result in a bigger sizing of the heat exchanger, hence the methanol is recirculated to the phase separator. The corresponding operating points 4, 5 and 6 in Figure 8 showcase the process of compression and expansion in the cooling cycle. In this case, the ram air channel controller ensures that a satisfactory upper pressure level p_{high} is maintained, while the compressor ensures the load reaches its target temperature, effectively controlling the lower pressure level p_{low} . The coolant pump again ensures that a desirable vapor fraction is obtained at the fuel cell outlet.

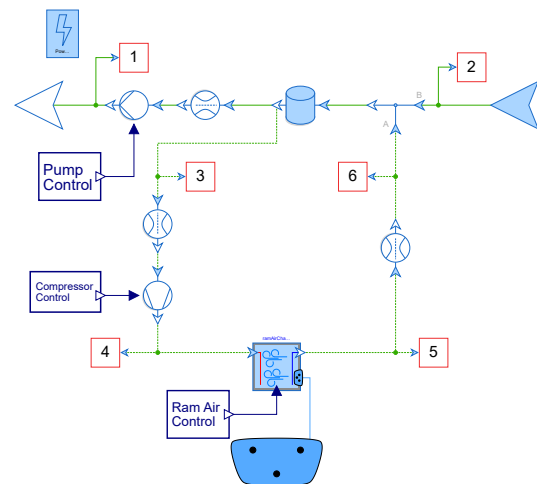


Figure 10. Methanol cooling cycle, including a compressor to increase the condenser inlet methanol temperature to improve cooling efficiency.

3.4 Vapor Compression Cooling

Besides the direct two-phase cooling in terms of evaporative cooling, an indirect two-phase cooling concept using a vapor compression system (VCS) was investigated. This system consists of two combined cycles - a conven-

tional liquid cooling cycle and a VCS, as shown in Figure 11. The VCS consists of four main components, a compressor, condenser, expansion valve and evaporator. The compressor brings the refrigerant to higher pressure and temperature to ensure heat rejection to the ambient by condensation in the condenser. The expansion valve subsequently expands the refrigerant to a lower pressure and temperature to absorb heat during evaporation in the evaporator. On the secondary side of the evaporator, the refrigerant absorbs the heat from the liquid coolant that is used to control the fuel cell temperature.

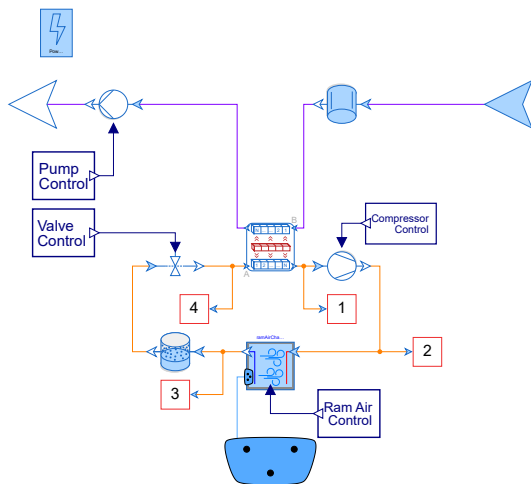


Figure 11. Vapor compression cooling system, consisting of two separate loops. The purple loop contains a purely liquid coolant, while the orange loop utilizes a phase changing refrigerant.

In the present system we make use of a high temperature refrigerant (HFO-1336mzz-Z) that enables a high condensation temperature in the condenser. We assume, that this will result in advantages with regard to the design of the heat exchanger and the dimensioning of the ram air duct in comparison to conventional refrigerants. The very low global warming potential (GWP) of the refrigerant makes it additionally interesting for applications in aviation. In principle, however, indirect two-phase cooling can also be achieved with conventional refrigerants. A detailed analysis of the advantages and disadvantages in terms of dimensioning and operation is still pending. In this system, the pump of the liquid coolant once again ensures a constant temperature difference across the fuel cell. The ram air channel controller keeps the upper pressure level of the VCS to uphold a sufficient temperature difference to the ambient air. The lower pressure level and hence the evaporation temperature is controlled by the compressor. Contrary to conventional VCS, we use the expansion valve to ensure sufficient refrigerant flow through the cycle to maintain the fuel cell target temperature instead of controlling the evaporator superheating (Michalak, Emo, and Ervin 2014).

4 Aircraft and Mission Profile

Several cooling systems were tested throughout an exemplary flight mission for a fuel cell driven electric aircraft. The reference architecture is derived within the DLR internal EXACT project (*EXACT – Conceptual study for future climate-neutral flight* n.d.) and is shown in Figure 1. It is a fully fuel cell driven aircraft for 70 passengers. The fuel cells are directly integrated in the nacelle and a total number of 10 pods is distributed across the wings. The total required shaft power of all pods combined at the corresponding altitude is shown in the mission profile in Figure 12.

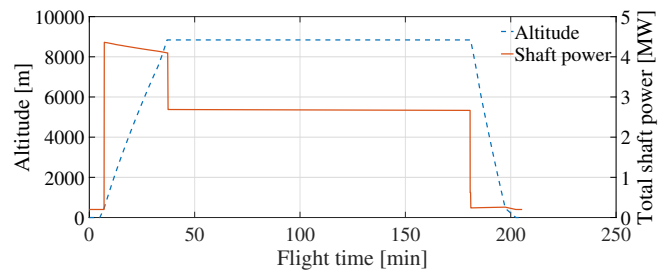


Figure 12. Mission profile with altitude and total required shaft power.

The total flight time is around 200 min and a maximum speed of Mach = 0.55 is reached during cruise at an altitude of 8840 m. The mission profile covers the main flight phases taxi out, take-off, climb, cruise, descent, approach, landing and taxi in. Ambient pressure and temperature are derived from the ISA standard conditions (15 °C on ground).

5 Simulation Results

In the following section, the results of the mission simulations will be presented. It has to be mentioned, that this paper focuses on the functionality of the TFS and the goal was to prove that a variety of different cooling systems with different coolant media can be quickly built up and tested throughout a flight mission. We are not yet in the state to make definite statements on the performance of each cooling system. This would assume not only a detailed sizing of each of the components but also an optimized control strategy. Nevertheless, we were able to simulate all of the cooling systems described in Section 3 through the fast changing operating points of a flight mission while reaching the desired fuel cell target temperature of 80 °C. As the systems differ in the number and arrangements of the components, some common variables of the cooling systems were compared. One important indicator of the performance of a cooling system is the amount of ambient air that was required to reach the fuel cell target temperature. A high demand of ram air flow has significant impact on the total drag that is induced on aircraft level. The airflow through the ram air channel for each cooling system is shown in Figure 13.

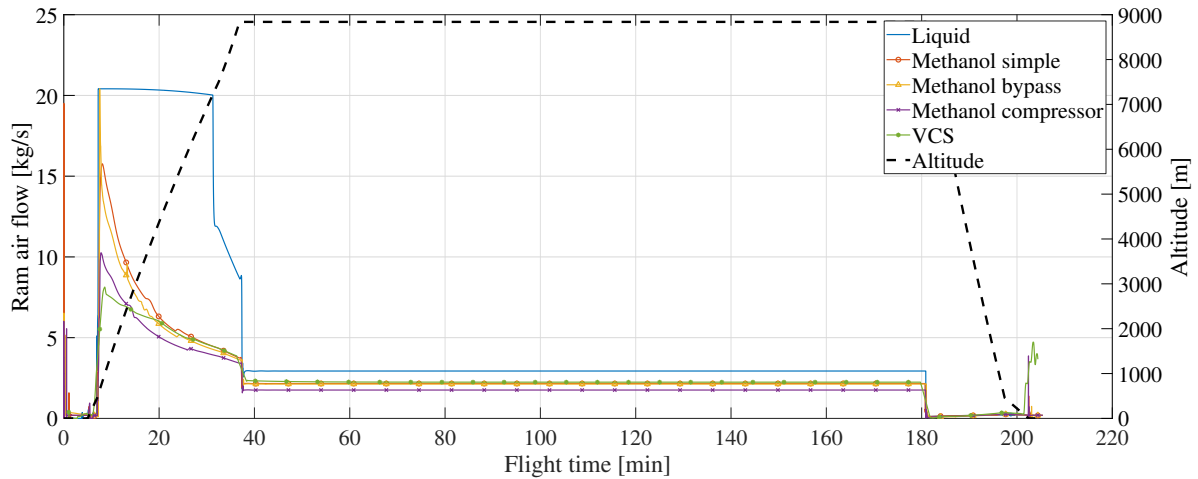


Figure 13. Required ram air flow of different cooling systems during flight mission.

It is noticeable, that the liquid cooling system requires significantly more ram air during the climb phase. This is due to the previously discussed small temperature difference of the ambient to the coolant. Especially in this flight phase, the advantages of the methanol cycles become clear, as the required ram air flow is drastically reduced. Also the benefits of the methanol cycle with the compressor to increase the condenser inlet temperature are clearly visible as it requires the least ram air flow during the climb phase. Different from our simulation, the EX-ACT aircraft concept includes a battery that serves as a booster in this critical flight phase and therefore could decrease the required power from the fuel cell. This would result in less heat that has to be removed and hence a smaller amount of required outside air. At the very end of the flight mission, an increase in required ram air flow can be observed for the VCS cooling system. This is mainly due to inefficient control and operation of the VCS since the set-points are not dependent on the flight phase yet.

Another indicator of the performance of the cooling system is the power that is required by the turbomachines and pumps of each system, including the air supply. In Figure 14 the accumulated energy that is consumed by a number of 10 propulsion nacelles throughout the mission is shown for each cooling system. It has to be mentioned, that the air supply system consists of a turbine that regulates the pressure before the air enters the fuel cell. The turbine is mounted on the same shaft as the air compressor to recover energy from the fluid. The power that is generated by the turbine is also taken into account in the accumulated total energy. Remembering that the liquid cooling system required the largest amount of ram air flow for cooling, it seems beneficial in terms of energy consumption. The systems including a compressor turn out to be more energy consuming while requiring less ram air for cooling.

A conventional indicator regarding energy consumption and cooling efficiency is the so-called coefficient of performance (COP) which is usually calculated for VCS

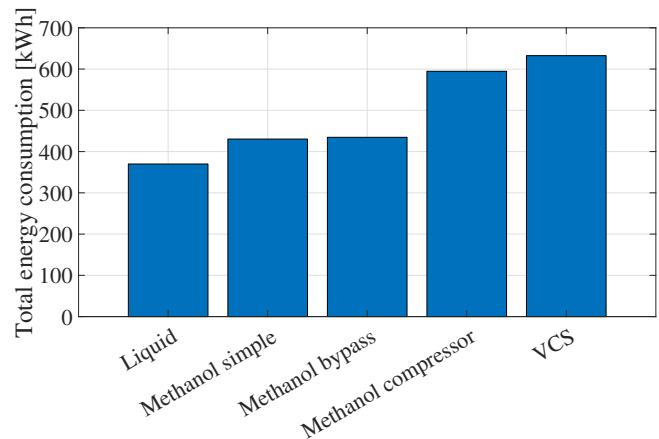


Figure 14. Accumulated total energy demand of different cooling systems during flight mission.

cooling systems. In the following, we want to have a closer look on the VCS and its operation during the flight mission. The COP is the ratio of the cooling power during the evaporation Q_{evap} process over compressor work W_{compr} :

$$COP = \frac{Q_{evap}}{W_{compr}} \quad (1)$$

Taking a closer look on the COP of the VCS throughout the flight mission (Figure 15), the relatively high numbers need some explanation. VCS systems in aviation are usually beneficial during ground or low altitude conditions, when the ambient temperature is still relatively high. Therefore the high temperature for heat rejection into the ram air channel can be exploited.

Most of the time during the mission, especially during cruise, the VCS runs in a degenerated operating mode because of the very low ambient temperature. This results in a very low compressor work, as the condensing temperature and hence the high pressure level of the VCS can be

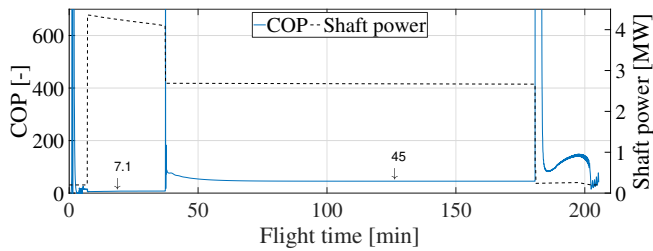


Figure 15. COP of VCS and total required shaft power during flight mission.

very low compared to normal operations. Consequently, the evaporation process takes place on a similar pressure and temperature level as the condensation process, resulting in a very high COP. Additionally, the sudden drops in the total shaft power after top of climb and in the transition from cruise to descend are leading to very high peaks in COP which goes up to values of a few thousands, which means that the compressor runs on the absolute minimum. Due to visualization reasons, the peaks are cut off in Figure 15. Those degenerated operating modes promised to be challenging to tackle in our simulations, because it results in very low refrigerant mass flow that can lead to instabilities. Strategies like including a bypass around the condenser to reduce the heat transfer rate (head pressure control) while keeping a minimum refrigerant flow are currently under investigation.

All the presented results still have to be taken with care, as a detailed sizing of the compressors, heat exchangers, ducts and also the ram air channels was not yet carried out. Anyway it still points out, that the selection of an optimal cooling system for the thermal management of the fuel cell is a complicated task with many influencing factors.

6 Conclusion

The objective of this work was to build up an aircraft fuel cell system and its subsystems with components of the TFS. The focus was on the rapid testing of different cooling systems in the environment of the overall fuel cell system throughout a whole flight mission. Common interfaces were defined that enable a quick interchangeability of the system architectures. A prototypical control scheme was developed for each cooling system to maintain a fuel cell target temperature during all operating points. This work should serve as a basis for future investigations on the benefits and drawbacks of specific cooling architectures. For more reliable statements on the performance of different systems, a more detailed sizing of the components as well as optimized control strategies will be subject to future research activities. This also refers to the air and LH2 supply systems as well as the drive train that is planned to be expanded by a battery model. In addition to that, the water separation process, that is important for the exhaust gas handling, is also intended to be improved by providing a model of a membrane humidifier. Nevertheless, the robustness of the TFS proved to be crucial during

the development of thermal systems with such complexity.

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