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In this work, the control scheme of the hydrogen solid oxide fuel cell (SOFC) propulsion system of the DLR-internal project H2EAT is presented. The application of this system is planned for a regional aircraft with an entry-into-service in the year 2050. For the operation of the fuel cell, it is necessary to control multiple variables such as the pressure, the mass flow and the electric power output. Additionally, the temperature gradient, both spatially and temporally, is of paramount importance. Strict temperature gradients have to be complied in order not to damage the fuel cell. The control system is realized by implementing PI controllers as they are favorable for an integrated system due to their low computational effort. The considered fuel cell system operates a pressurized fuel cell stack together with a combustion chamber after the SOFC to burn the excess hydrogen. A turbine then partly recuperates the heat energy by relaxing the exhaust gas stream to ambient conditions. Dynamic simulations over an aircraft mission are performed within the framework of Modelica and the in-house, open source ThermoFluidStream (TFS) library. The control scheme presented in this work is well suitable to operate the fuel cell system over the complete mission. Although small improvements can be made to the control of the temperature gradients and the control of the pressure level.

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Control Scheme of a Solid Oxide Fuel Cell System for Regional Aircraft

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In this work, the control scheme of the hydrogen solid oxide fuel cell (SOFC) propulsion system of the DLR-internal project H2EAT is presented. The application of this system is planned for a regional aircraft with an entry-into-service in the year 2050. For the operation of the fuel cell, it is necessary to control multiple variables such as the pressure, the mass flow and the electric power output. Additionally, the temperature gradient, both spatially and temporally, is of paramount importance. Strict temperature gradients have to be complied in order not to damage the fuel cell. The control system is realized by implementing PI controllers as they are favorable for an integrated system due to their low computational effort. The considered fuel cell system operates a pressurized fuel cell stack together with a combustion chamber after the SOFC to burn the excess hydrogen. A turbine then partly recuperates the heat energy by relaxing the exhaust gas stream to ambient conditions. Dynamic simulations over an aircraft mission are performed within the framework of Modelica and the in-house, open source ThermoFluidStream (TFS) library. The control scheme presented in this work is well suitable to operate the fuel cell system over the complete mission. Although small improvements can be made to the control of the temperature gradients and the control of the pressure level.

I. Introduction

The aviation industry is moving towards more environmentally friendly technologies by introducing more electric aircraft and the use of alternative fuels such as sustainable aviation fuels or hydrogen. The German Aerospace Center (DLR) is following this trend with multiple projects. One of these is the DLR-interal project H2EAT which considers a hydrogen powered solid oxide fuel cell (SOFC) as the main energy source for the propulsion. Although the amount of research performed about SOFC in aviation is increasing, the technology itself is still in an early stage and hence at a low technology readiness level. The aim of the project is to power a regional aircraft with a total power of roughly 4 MW for an entry into service in the year 2050. The main goal is to compare a nacelle integrated and a fuselage integrated concept with distributed electric propulsion along the wing [1].

Many earlier studies focused on the application of SOFCs as auxiliary power unit (APU) of an aircraft. This application was analyzed by [2] for a regional aircraft and by [3] for a Boeing 787. The results yielded a weight disadvantage of the SOFC which might be compromised by fuel savings that are an effect of higher efficiencies. Additionally, [4] provides a comprehensive review of many studies about SOFCs as APU. A recent work studied the propulsion of a regional aircraft powered by a hybrid hydrogen fuel cell and gas turbine powertrain. The dynamic simulations of a complete aircraft mission provided results of about 1.3 MW power output and efficiencies of up to 71.4% [5].

A similar system to the latter shall be considered in this work. Dynamic simulations of the fuel cell system are carried out to design a control system for the proposed powertrain architecture. For this, the modelling language Modelica together with the in-house developed, open source ThermoFluidStream (TFS) library by the DLR [6] provide a suitable framework. The TFS includes low fidelity, physics based models of compressors, turbines, heat exchangers etc. In a previous work [7], a dynamic fuel cell model was developed following the approach of the TFS. The thermodynamic aspects of a fuel cell and the governing electrochemical equations are considered to perform multi-domain simulations over a whole aircraft mission. In the work, it was shown that the fuel cell model is capable of doing so. However, the fuel cell system was kept very simple including a control scheme for the mass flow, the pressure and the electric power output of the fuel cell, while analyzing this control system was not the focus of the work. Additionally, a thermal management system (TMS) was neglected. Hence, the goal of this work is to analyze the control scheme while extending it for a thermal management. Hereby, not only the temperature of the reactants at fuel cell inlet is considered, but also the

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temperature difference over the fuel cell stack is taken into account. In a real system, this is needed to keep the spatial temperature gradient low enough. Otherwise, the fuel cell would be damaged by thermal fatigue shortening the lifetime [8]. The temporal temperature gradient, which is as important as the spatial temperature gradient, is analyzed as well. As widely considered, the TMS is realized with a surplus of cathode air. Another goal is to use PI controllers that need only low computational effort which is favorable for the integration in an aircraft.

In the following, the simulation setup and the control scheme of the proposed fuel cell system are presented. Additionally, the inputs of the aircraft mission for the simulation are shown. With this setup, dynamic mission simulations are carried out. Subsequently, the results of the simulations are discussed with the focus on the control scheme. Hereby, strengths and weaknesses of the control are pointed out as well as critical aspects.

II. Simulation Setup

As mentioned above, the considered powertrain shall have a total power output of up to 4 MW which is planned to be distributed over several fuel cell systems. The simulation model is built assuming four parallel, identical fuel cell systems with one stack and 1 MW power output each. One such system is depicted in Figure 1.

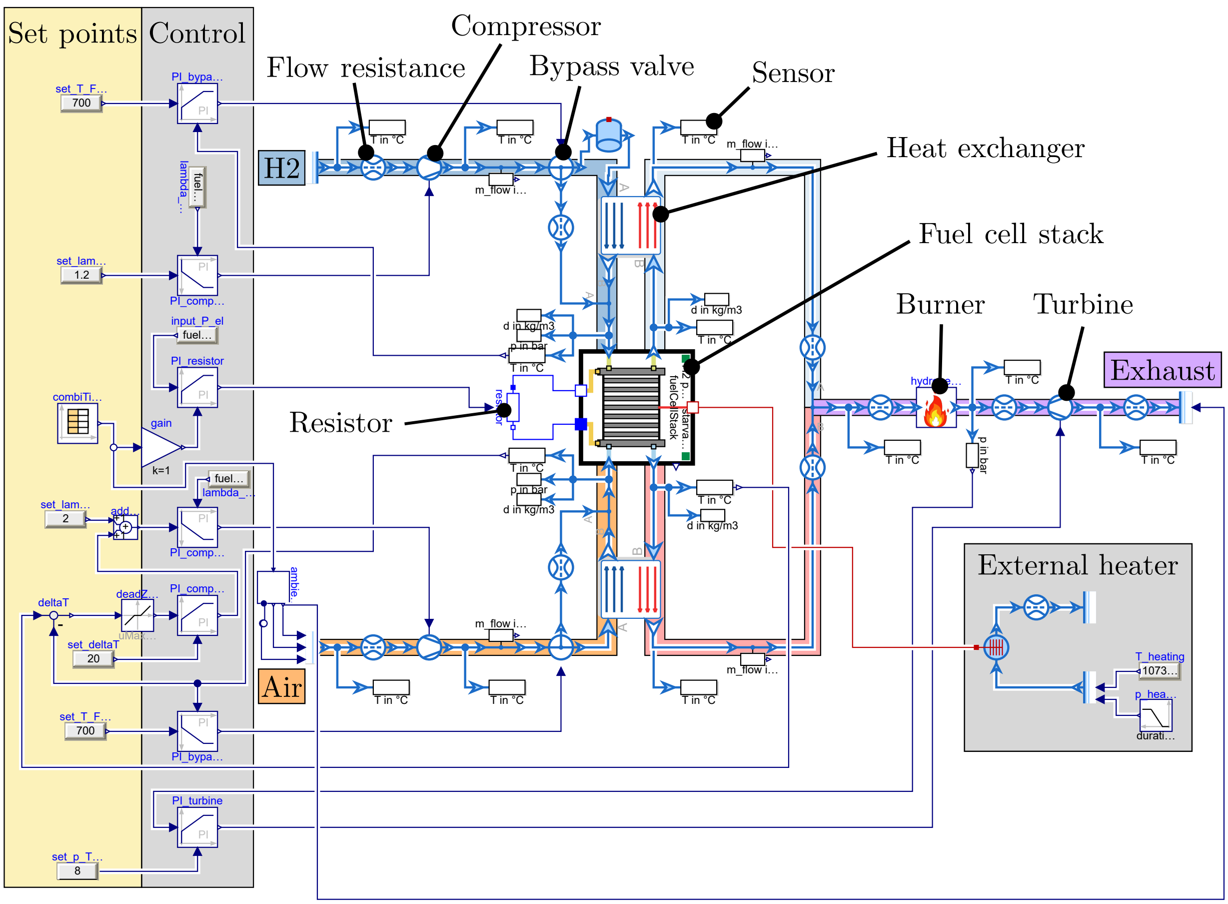


Fig. 1 Simulation setup of the fuel cell system and its control scheme in Modelica.

The blue envelope marks the hydrogen path where gaseous hydrogen is provided at 23.15 K which is 2 K above the boiling temperature [9]. The fuel is pressurized by a compressor and heated up by a heat exchanger using the heat of the anode exhaust gas. Over the bypass around the heat exchanger, the temperature at the fuel cell inlet can be adjusted. The same preconditioning is done for the air, which is highlighted in orange. At the source, air is provided at ambient conditions. The latter are calculated with the altitude, which is defined by the mission, and the international standard atmosphere (ISA) according to [10]. After the fuel cell outlet and after heating up the reactants, the two exhaust gas streams are combined to burn the residual hydrogen in a combustion chamber. Ultimately, the turbine partly recuperates

Table 1 Set points of the control scheme.

Control Variable	Set Point	Unit	Actuator
Pressure level	8	bar	Turbine
Hydrogen surplus ratio	1.2	-	Hydrogen compressor
Oxygen surplus ratio	2	-	Air compressor
SOFC anode inlet temperature	700	°C	Hydrogen bypass valve
SOFC cathode inlet temperature	700	°C	Air bypass valve
Electric power output	various	W	Variable resistor
Fuel cell temperature difference	max. 200	K	Air compressor

the heat introduced by the combustion by relaxing the stream to ambient conditions. The external heater in the grey box is only active in the beginning of the simulation to heat up the stack since a start-up capability of the architecture is not considered in this work.

For the operation of the fuel cell, the mass flow, the pressure and the temperature of the reactants need to be controlled as well as the electric power output. Hereby, the compressors and the turbine can be used to control the pressure and the mass flow, assuming they are not directly connected mechanically. The turbine is used to control the pressure level, since the pressure should be the same in the complete system to not damage the fuel cell. Hence, the compressors are used to control the mass flow of each reactant. The mass flow control is realized by controlling the surplus ratio λ_i of the reactants i which is defined as

$$\lambda_i = \frac{\dot{m}_{i,in}}{\dot{m}_{i,cons}} \tag{1}$$

with the inlet mass flow $\dot{m}_{i,in}$ and the mass flow $\dot{m}_{i,cons}$ of consumed reactant. Furthermore, the temperature control is done by adjusting the bypass ratio of the stream around the heat exchanger, assuming that the latter can always provide more heat than needed to achieve the desired fuel cell inlet temperature. Besides these control variables, there is one important constraint on the temperature difference between fuel cell inlet and outlet at the cathode side of the SOFC. This temperature difference represents the spatial temperature gradient over the stack which should not exceed a specific threshold in order to limit thermal fatigue over the lifecycle of the fuel cell. This is realized by introducing a control cascade for the mass flow control at the cathode side, i.e. at the air side. If the temperature difference is low enough, only the inner loop of the cascade is active which adjusts the surplus ratio of oxygen to a constant level. If the temperature difference rises above a certain threshold, the outer loop becomes active and adds to the input value of the inner loop to increase the surplus ratio. Consequently, the air mass flow is increased which cools the fuel cell. Additionally, the electric power output of the fuel cell is controlled by changing the resistance of a variable resistor which is connected to the stack. This is a simple way of representing the DC/DC converter and the remainder of the power electronics. An overview of the control scheme is given in Table 1 with estimated values for the control variables. Although not a control variable but a constraint, the temperature difference is listed as well.

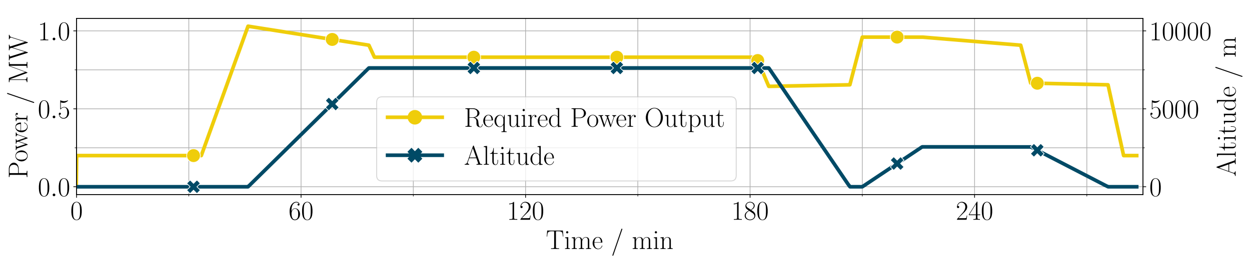


Fig. 2 Turboprop mission definition consisting of the altitude and the required power output.

The mission considered in this work represents an exemplary turboprop aircraft mission with the corresponding power output and altitude profile shown in Figure 2 including a reserve mission in case of a touch and go maneuver. Hereby, the power output is the input variable for the control of the electric power output of the fuel cell and the altitude is used to calculate the ambient conditions for the air inlet and the outlet. The maximum altitude is 25000 ft or 7620 m. The maximum power is 1.03 MW. The ramp up of the power output is adjusted for the simulation to run more robustly. Herefore, the assumed power for the taxi phase is held for longer than the taxi phase would last in a real application to equalize the effects of initializing the simulation at ambient conditions. This initialization is common practice in Modelica and the TFS but not trivial for large simulation models as the one considered here. During the prolonged taxi phase, the external heating is active to heat up the fuel cell to an average temperature of 700 K. Additionally, the ramp of the required power between the taxi phase and the take-off phase is prolonged to allow for slower ramping up the fuel cell system. Further research is necessary to approach the startup procedure with slow transients of the SOFC which is currently a problem for an application in aviation. However, this shall not be the focus of this work.

III. Results and Discussion

As mentioned above, the control of the surplus ratios of the reactants, the pressure level and the power output was briefly presented in a previous work. However, it was only used to show an exemplary application of the fuel cell model, but the control scheme was not analyzed. To do so, the corresponding control variables with measured value and set point over the mission time are shown. First, this is depicted for the surplus ratio of hydrogen in Figure 3. The grey line represents the required power output. This is done here, as well as in almost every following plot, to give an orientation about the mission. Figure 3 shows that the measured value only deviates in situations where the power of the SOFC is changed. The occuring deviations are not considered a problem. Hereby, the most critical aspect would be the surplus ratio reaching values of one and below by which the fuel cell would be damaged due to fuel starvation. The lowest values occuring at 1.17 stil have a good margin above this threshold. Ratios higher than the set point are assumed to be noncritical, especially in the range occuring here, since the concentration of hydrogen at the fuel cell outlet is higher. This results in more hydrogen being burned in the combustion chamber. At the obtained peak values of 1.23, this would merely affect the performance of the system and it is noncritical. Hence, the control of the surplus ratio is considered to operate well.

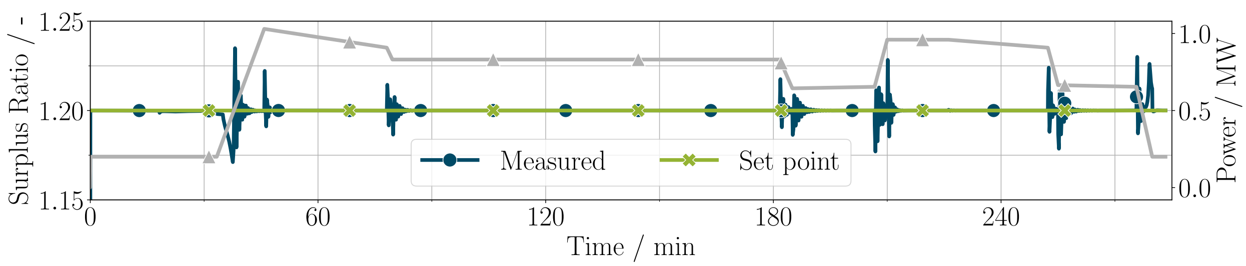
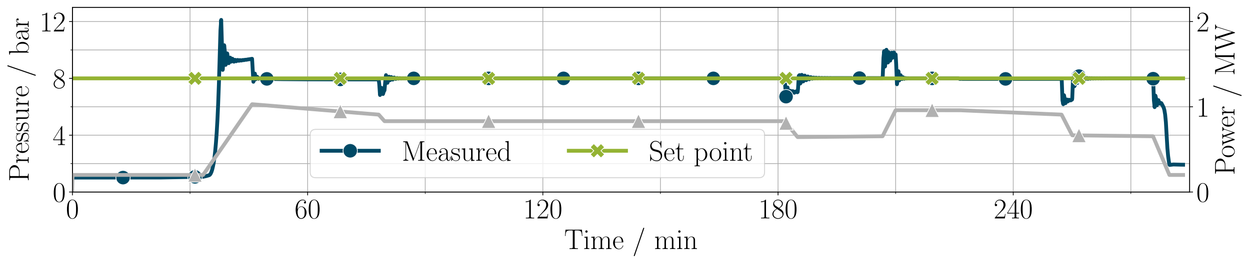
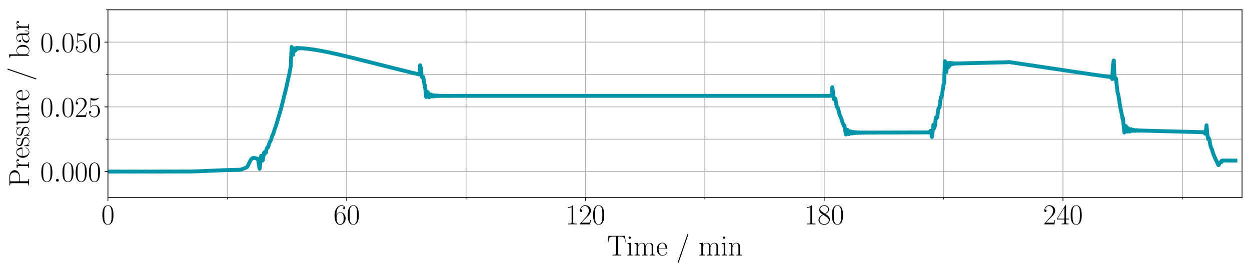


Fig. 3 Analysis of the control of the hydrogen surplus ratio over the mission time; the required power output is shown in grey as orientation.

The distribution of the control of the pressure level in Figure 4a looks similar to the control of the surplus ratio since the set point is constant as well and deviations occur in dynamic situations. With peak values of up to 4 bar in the beginning of the simulation and up to 2 bar during the remainder of the mission, these deviations are more significant with regard to the set point. This is not ideal for the operation of the system, e.g. for the compressors as especially higher pressures could result in stalling them. The high peak is obtained because the time constant of the controller of the turbine is much smaller than the time constant of the controllers of the compressors. This is necessary because oscillations occur, if the time constants are similar. Also, if the time constants of the controllers of the compressors are much higher than the controller of the turbine, the surplus ratio of hydrogen reaches critical values of one. Therefore, the last option is not applicable. This issue is expected to be solvable with further parameter tuning. However, the fuel cell should not be damaged since the critical aspect in terms of pressure is the pressure difference between anode and cathode. This is a major benefit of realizing the control of the pressure level with the turbine. The pressure difference over the SOFC is presented in Figure 4b. The occuring peak values of roughly 0.051 bar are not considered critical for the fuel cell stack. The pressure difference comes from the compressors and is necessary to adjust the mass flow of each reactant properly. The low pressures in the beginning and in the end of the mission in Figure 4a are obtained due to the big difference in mass flow and volume flow, respectively. As the turbine is sized for higher volume flows which occur during the cruise phase, it can not build as much pressure in low power conditions, i.e. in low volume flow conditions,



(a)



(b)

Fig. 4 Analysis of the pressure control over the mission time with (a) the absolute pressure at the turbine inlet and (b) the pressure difference between the anode and the cathode inlet of the fuel cell stack.

as it is currently modeled.

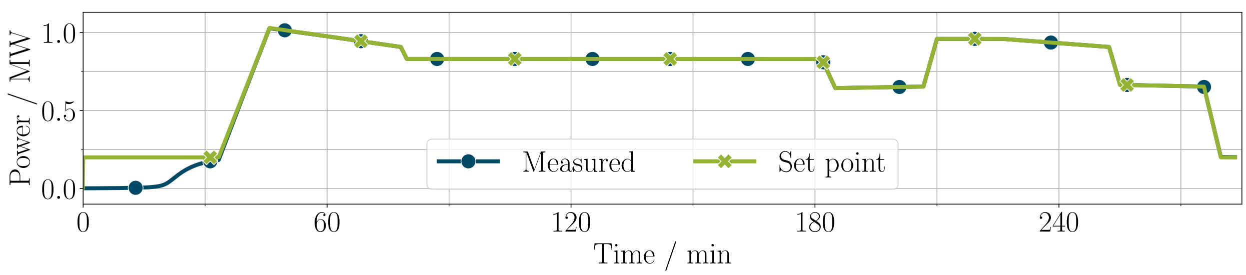
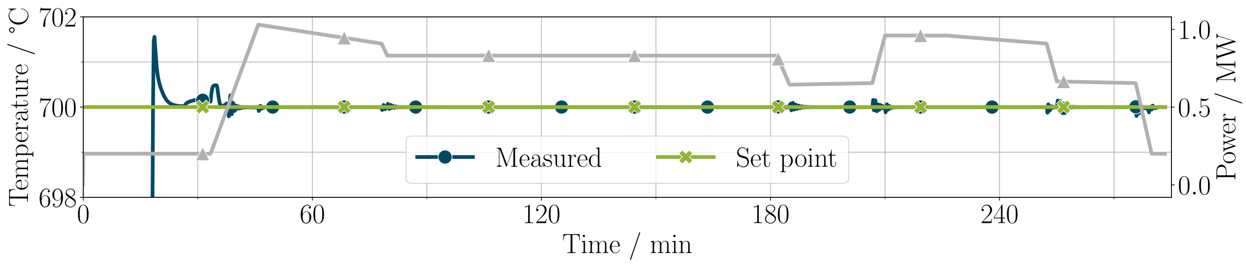


Fig. 5 Analysis of the control of the electric power output of the fuel cell stack over the mission time with.

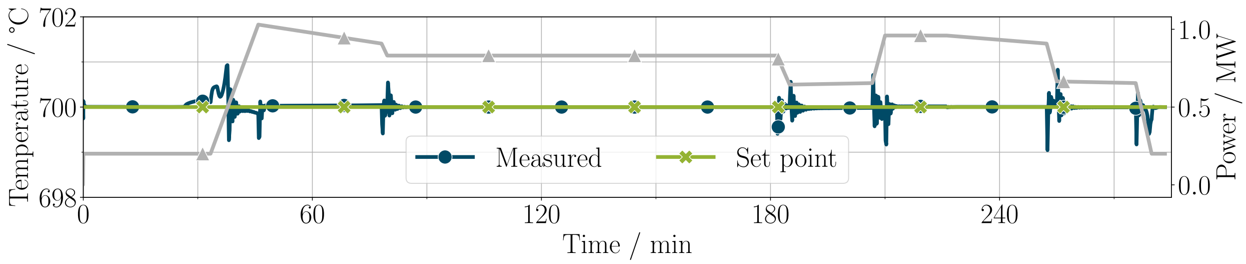
Regarding the control of the electric power output of the fuel cell stack, there is a major difference between the set point and the measured value in the beginning of the mission as displayed in Figure 5. This is due to the slow transients and hence a slow startup procedure of the SOFC, as mentioned in section II. This startup procedure is not the focus of this work. However, to solve this issue, there will be batteries included in the powertrain which are capable of compensating for the slow transients of the SOFC. For the remainder of the mission, the control works very well. This will be similar in an integrated system since the transients of electric systems are generally much faster than the transients of the fuel cell system.

The temperature control and the corresponding variables are presented in Figure 6. Both, the anode temperature as shown in Figure 6a and the cathode temperature in Figure 6b stay within an envelope of 1 K difference to the set point when neglecting the startup of the system before the 25 min mark. The thermal stresses resulting from these temperature differences are assumed to be very low. Therefore, the temperature gradients in the fuel cell, both spatially and temporally, are considered to be noncritical and the control approach is considered to be suitable for this application.

Lastly, the control of the spatial temperature difference between the cathode inlet and the cathode outlet, which is directly linked to the spatial temperature gradient, is shown in 7a. In the beginning of the mission the controller is inactive since the temperature is below the threshold of 200 K. After roughly 35 min the controller becomes active. Besides the initial overshoot of 12.2 K of the temperature difference, the set point is met well with a maximum deviation of +3.2 K. Hereby, only larger temperature differences are critical. Lower differences which occur e.g. in the end of the



(a) Anode inlet temperature.



(b) Cathode inlet temperature.

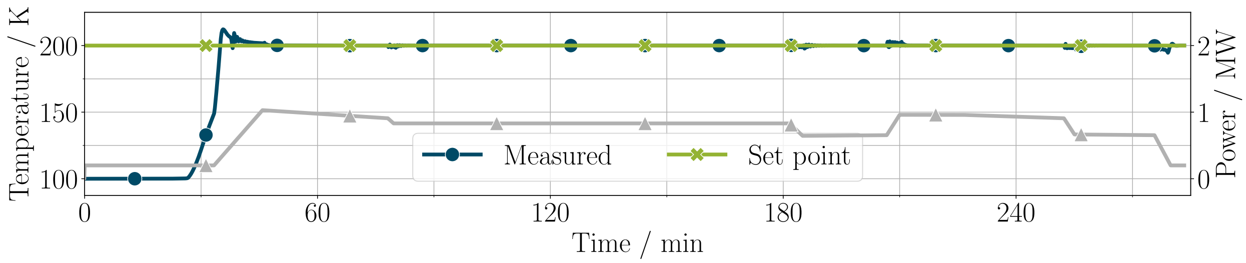
Fig. 6 Control of the temperature at the fuel cell inlet over the mission time for the anode in (a) and the cathode in (b).

mission with up to 5.4 K are noncritical since lower temperature differences are always better. The only critical aspect would be a high temporal temperature gradient. This temporal temperature gradient of the average fuel cell temperature is presented in Figure 7b. Since the spatial temperature gradient over the channel length of the SOFC is almost linear according to [11], the average temperature is calculated as the difference between the cathode inlet and the cathode outlet of the stack under good approximation. With a value of 0.43 K/min, the temporal temperature gradient is well below the range of 5 - 10 K/min which is considered critical according to [8]. However, different options to minimize the initial peak of the spatial temperature difference are recommended such as to further tune the controller or to lower the set point to have a larger margin to the threshold.

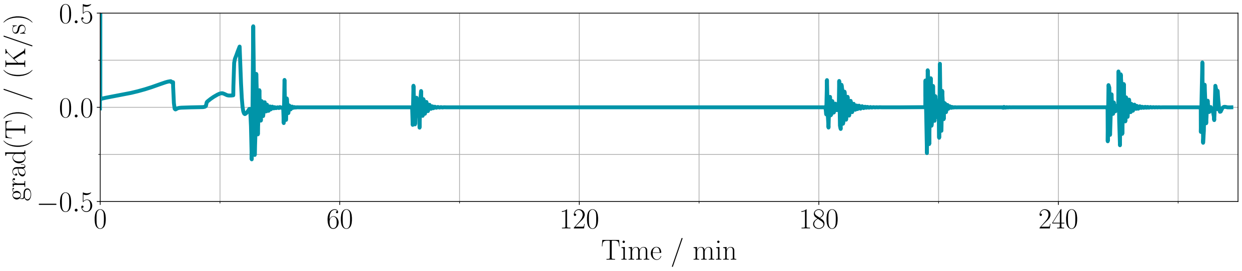
The control of the spatial temperature gradient as the outer loop of the control cascade influences the set point for the surplus ratio of oxygen as the inner loop. Hence, the surplus ratio, presented in Figure 7c, changes throughout the mission. Hereby, the measured value follows the set value very well. Similar to the surplus ratio of hydrogen, only a ratio of 1 or lower would damage the fuel cell. Since the surplus ratio of oxygen is multiple times higher than this threshold due to the added surplus of the temperature gradient control, the deviations are noncritical.

IV. Conclusions

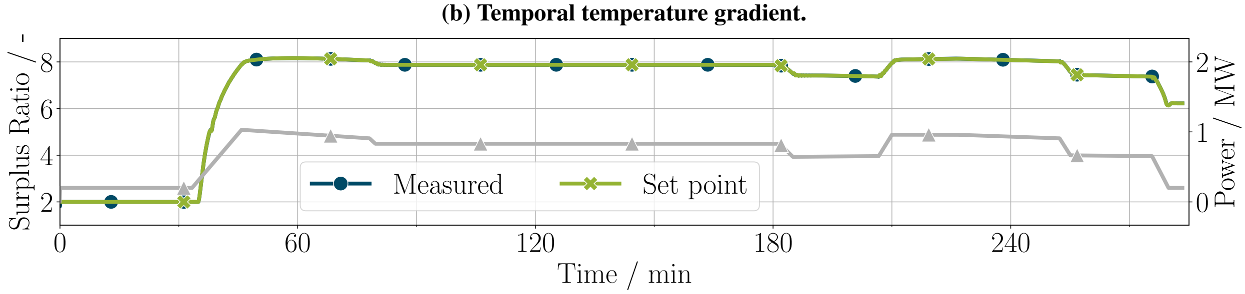
The presented control scheme is well suitable for the operation of the considered fuel cell system. It is capable of operating the fuel cell and the corresponding balance of plant components over the duration of a whole aircraft mission including a reserve mission in the case of a touch and go maneuver. The small issues that are left, e.g. the high overshoot of the pressure and the spatial temperature gradient, are expected to be solved by parameter tuning. Although only PI controllers are used in this approach, the set points are met well. Hereby, the use of PI controllers in a real integration is beneficial because it keeps the necessary computing power small when compared to more elaborate controllers such as model based feed forward or model predictive control. Especially the control of the surplus ratio of both, hydrogen and oxygen, the control of the inlet temperature of the fuel cell at the anode and the cathode and the control of the power output are working well. However, small adjustments are recommended for the control of the pressure level and the control of the spatial temperature gradient. The obtained results indicate that critical operation points could occur e.g. for the compressors due to high pressures. Furthermore, the spatial temperature gradients should be kept smaller to minimize the thermal fatigue of the fuel cell stack over its lifecycle.



(a) Spatial temperature difference.



(b) Temporal temperature gradient.



(c) Surplus ratio of oxygen.

Fig. 7 Analysis of the cascaded control of the air compressor with the spatial temperature difference in (a), the temporal temperature gradient of the average fuel cell temperature in (b) and the surplus ratio of oxygen at the cathode inlet in (c).

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