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Grant No.: 641073

Bio-HyPP

Deliverable No	**Title**	**Submission Due Date**	**WP/Lead**
D4.3	Characteristics of the hybrid power plant with emulated SOFC	30.04.2019	WP4 / DLR
Short Summary	This document describes the deliverable D4.3 "Characteristics of the hybrid power plant with emulated SOFC" For the development of a hybrid power plant an MGT test rig based on a real MGT with emulated SOFC has been set-up and characterized. This was done to investigate the behaviour of the MGT under hybrid conditions, determine the stable operation range, develop transient manoeuvers and analyse limitations and critical manoeuvers without harming the SOFC system. In this deliverable the results of these investigations are shown.		
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Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
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List of Acronyms

C	Compressor
CO	Carbon monoxide
CO_2	Carbon dioxide
D	Deliverable
DLR	German Aerospace Center
Dp	pressure loss
El	Electric
η	efficiency
H_2	Hydrogen
H_2O	Water
HiL	Hardware in the loop
HyPP	Hybrid power plant
HSG	Hot steam generator
LHV	Lower heating value
$\dot{m}$	Mass flow
m_p	reduced mass flow
MGT	Micro gas turbine
MGT test rig	Hybrid power plant test rig consisting of real MGT and emulated SOFC
MTT	Micro Turbine Technology B.V
N	Rotational speed
N_p	Reduced speed
N_2	Nitrogen
O_2	Oxygen
OP	Operating point
ox	oxygen
p	Pressure
PID	Proportional integral derivative
PLC	Portable logic controller
Π	Pressure ratio
SM	Surge margin
SOFC	Solid Oxide Fuel Cell
SOFC test rig	Hybrid power plant test rig consisting of real SOFC and emulated MGT
T	Temperature
t	time
TOT	Turbine outlet temperature
WP	Work package

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1 Introduction

The aim of the Bio-HyPP project has been the development of a hybrid power plant [1] – a combination of a solid oxide fuel cell (SOFC) and a micro gas turbine (MGT). For this development, the understanding of both the characteristics of the MGT system and its components as well as the characteristics of the SOFC system and its components are essential. Transient manoeuvers like start-up, load change and shutdown have to be analysed and adapted for a combined operation. Critical events have to be investigated, emergency routines derived and developed. For the detailed investigation of both subsystems MGT and SOFC under hybrid conditions without harming the other system two separate test rigs have been set up as a part of WP4: the MGT hybrid power plant test rig (real MGT with emulated SOFC) and the SOFC hybrid power plant test rig (real SOFC with emulated MGT).

This report of D4.3 describes the system characteristics, the adaption of the transient manoeuvers and findings of the MGT hybrid power plant test rig. It is subdivided into four chapters.

Chapter 2 describes the objectives of the deliverable.

Chapter 3 shortly describes the test rig. Detailed information about the test rig, its installation and the control system can be found in [2], [3], [4] and [5].

In chapter 4, the experimental results are analysed and discussed.

Finally, Chapter 5 draws the conclusions.

2 Objectives and requirements

As part of WP4 "System Integration and Demonstration" the MGT test rig (real MGT with emulated SOFC) has been built and set-up in lab environment. The layout of the test rig, the control system and the components used for SOFC emulation are described in detail in [2], [3], [4] and [5]. The test rig has been characterized in two different layouts. In the first layout the original MGT recuperator and a combustor suitable for natural gas and biogas were used. Hereby, the focus was set on the general behaviour of the system and the development of transient manoeuvers. For the second layout the optimized components (WP2) combustion chamber and recuperator have been integrated into the test rig and after successful operation into the stand-alone MGT also the optimized power module was implemented.

To understand the reactions and interactions within this test rig, the experimental characterizations have been done to analyse the following:

- Steady state load points (from minimum part load to the maximum load point (base load))
- Characteristics of the components
- Operation range of the test rig and its components
- Limitations of operation range and during transients
- Transient manoeuvres
- Possible ramps for transients like in start-up, load change and shutdown
- Critical events
- Emergency routines

The analysis leads to the verification and to the adaption necessities of the concept of the hybrid power plant technology demonstrator.

Results of this deliverable are also used for the validation of the thermodynamic performance modelling (WP1) which is presented in deliverable D1.7 [9].

3 Hybrid Power Plant emulator test rig

3.1 Description of the test rig

The layout of the MGT test rig (real MGT with emulated SOFC) has been derived from the intended layout for the real coupled hybrid power plant. This real coupled plant layout is described in [1] and can be seen in Figure 1. Here, the SOFC is integrated in between MGT recuperator and combustion chamber and is therefore pressurized.

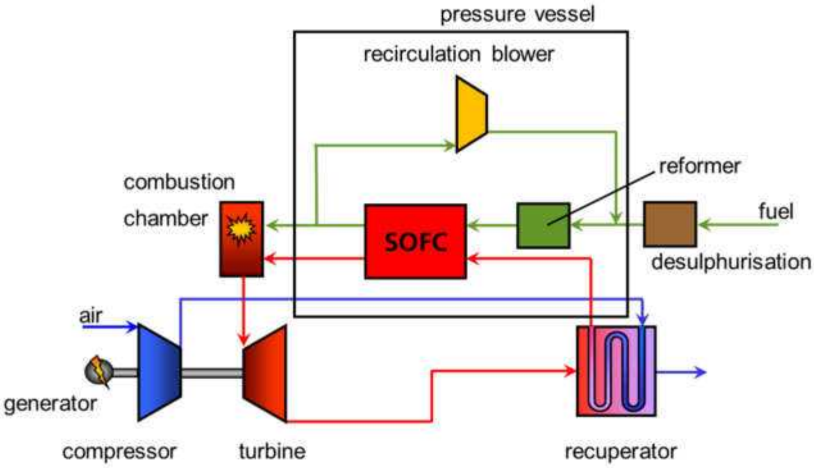

Figure 1: Plant Layout of the real coupled top-performance hybrid power plant [1]

For the layout of the MGT test rig, the MGT components have been kept as real operating hardware parts while the influences of the SOFC on the MGT are being emulated ([2] and [3]): temperature increase, pressure drop, retention time, SOFC off-gas composition and temperature. For the emulation of the SOFC off-gas with its high steam content, an additional device, the so called hot steam generator has been developed [12] and adapted to the test rig. It is composed of an H_2 and O_2 combustion chamber with downstream injection of CO and CO_2. For the emulation of the SOFC in the MGT test rig, two modes can be used: manual setting of parameters and a hardware-in-the-loop (HiL) model, described in [6].

A summary of the components for the SOFC emulation is given in Table 1.

Table 1: Emulation of SOFC influences in the MGT test rig [4]

SOFC emulation	Emulated by
Pressure drop and retention time through the pressure vessel of the SOFC	Pressure vessel
Temperature increase through the pressure vessel	Electrical heater
Pressure drop and retention time through the SOFC	Bend pipe
Temperature increase through the SOFC	Electrical heater
Composition and temperature of the SOFC off-gas into the combustion chamber	Hot steam generator (HSG)
Composition of the air outlet from the SOFC into the combustion chamber	Injection of nitrogen (N_2) into the inlet air

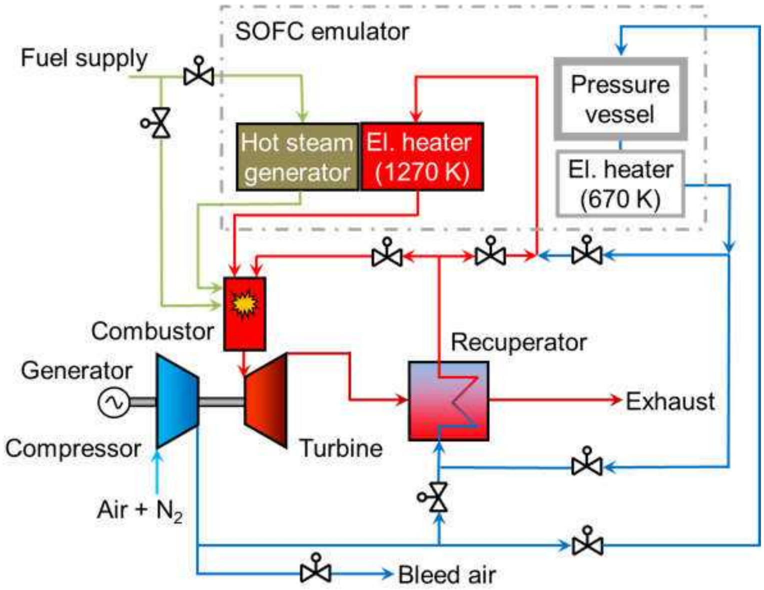

Figure 2: Plant Layout of the MGT hybrid power plant emulation test rig (real MGT with emulated SOFC) [3]

The overall schematic layout of the MGT test rig is represented in Figure 2 and the design of the test rig with the original components, paths and bypasses can be seen in Figure 3.

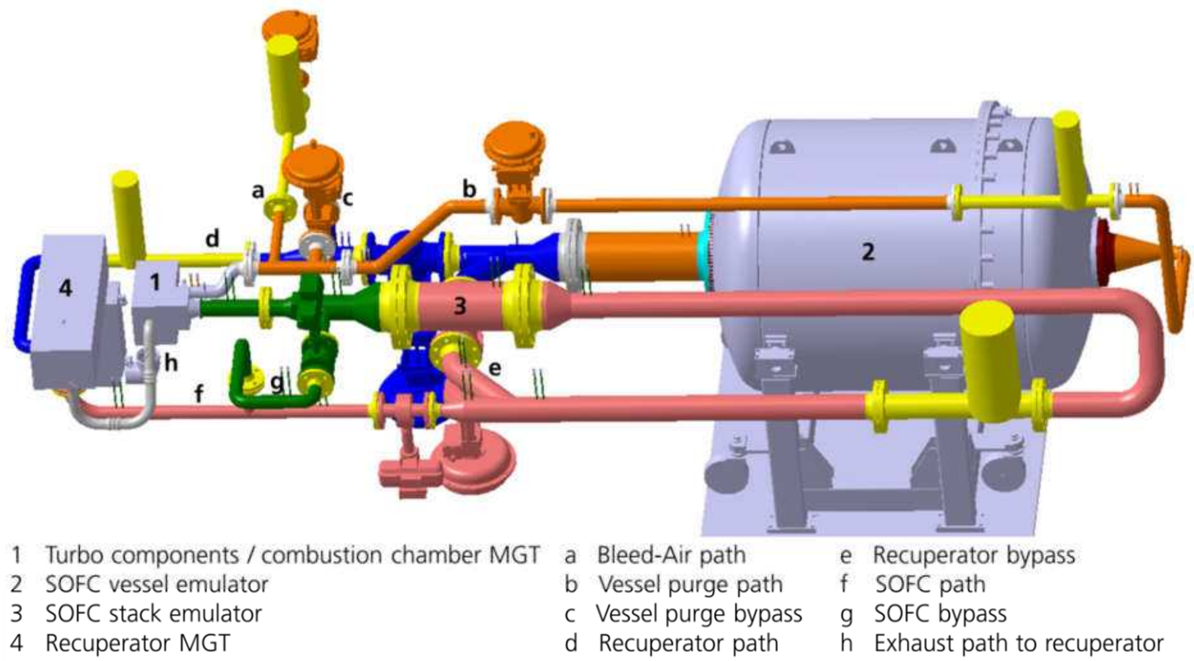

Figure 3: Engineered design of the MGT test rig [7]

3.2 Description of the control system

The control system of the MGT test rig was developed from the perspective of the real coupled hybrid power plant and is described in [4] and [5].

The system control contains:

- a state machine
- single control loops based on PID controllers
- safety reactions

The structure of the control system is described in [5] and the control loops are described in detail in [4].

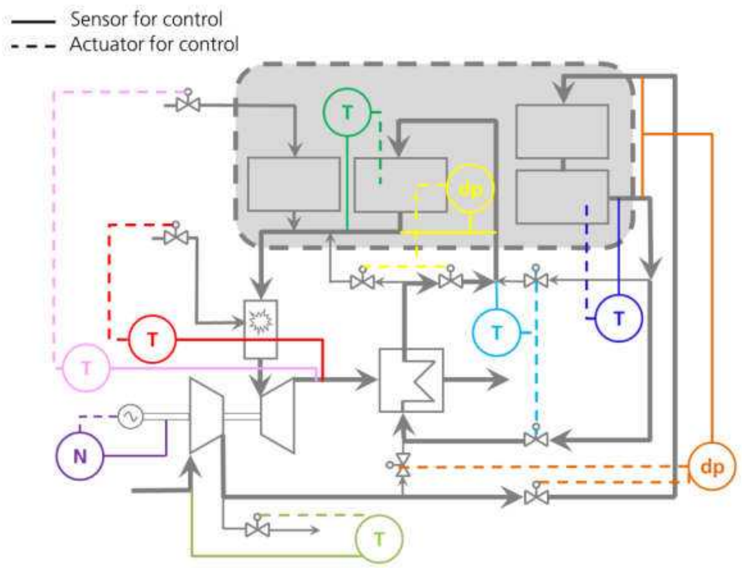

Figure 4: Control loops of the MGT system with emulated SOFC overlayed to the plant scheme (see Figure 2) [4]

Table 2: Purpose of the control loops of the MGT system with emulated SOFC [4]

Number	Control loop	Color
1	Turbine rotational speed	
2	Turbine outlet temperature (TOT) with natural gas	
3	Turbine outlet temperature (TOT) with off-gas emulator	
4	Temperature at cathode emulator inlet	
5	Temperature at vessel emulator outlet	
6	Temperature at cathode emulator outlet	
7	Pressure loss of vessel emulator	
8	Pressure loss of cathode emulator	
9	Temperature control at compressor inlet for surge detection	

The control character is part of the system characterization, as the system behaviour automatically includes the control reactions. Within the process of the experimental investigation, control loops have been developed for the use in a hybrid power plant and their parameters have been iteratively adapted to allow smooth running of the system.

4 Characterization

The characterization of the MGT system using an SOFC emulator is important to analyse the possible operational area of the MGT system, its boundary conditions, critical load points and the behaviour under hybrid conditions. Beside the overall system, the characteristics of the optimized components combustion chamber and recuperator have been investigated. These two components are essential for the integration of a MGT and an SOFC. Contrary to the requirements in a standard MGT, the pressure loss of the air side of the recuperator has to be minimized in a hybrid power plant. The combustor has to deal with a large variety of fuel compositions with lower heating values (LHV) from 1 to approximately 48 MJ/kg (SOFC off-gas to natural gas) for start-up, operation and shutdown of the system.

Besides the characteristics of the components, the control system is the crucial element adding to the transient characterization on one hand and needing to be adapted to cope with critical load points on the other hand. In the process of commissioning and testing, start-up, load change and shutdown procedures have been derived, adapted and analysed. In addition, procedures to cope with critical load points as well as emergency procedures to cope with external or internal failures have been developed.

Running experiments on the MGT test rig allows testing the characteristics without the danger of destroying a real SOFC which would be the case in a real demonstrator. This allowed a broad range of tests to analyse the limits of some components.

4.1 Characterization in steady state load points

The steady state load points are characterized in order to analyse the possible operational area. Each of the components has not only its own characteristic but is also influenced by the other integrated components. Therefore, the overall system characteristic is depending on the combination of the single component characteristics. The combustion chamber, the power module and the recuperator are the components with the strongest influence onto the whole system. They influence the possible operational area as well as the optimal load point for the system.

4.1.1 Turbo components - Compressor and turbine

The compressor is the most crucial component to the system characteristic, as the load point within the compressor map determines if the system runs in a stable condition or not. Compared to this fact, the influence of the turbine characteristic is relatively small. Turbine and compressor influence each other in their characteristics. Yet, the focus in the analysis has been towards the compressor.

A compressor is described by its compressor map, showing the lines of constant speed, the efficiency and the surge line in a graphical chart as a function of pressure ratio and corrected mass flow (Figure 5). The surge line and the surge margin (the distance of a load point to the surge line) are central to see if the compressor runs in a stable load point. The stable load point can only be achieved on the right side of the surge line. A stable operation on the left side of the line is not possible.

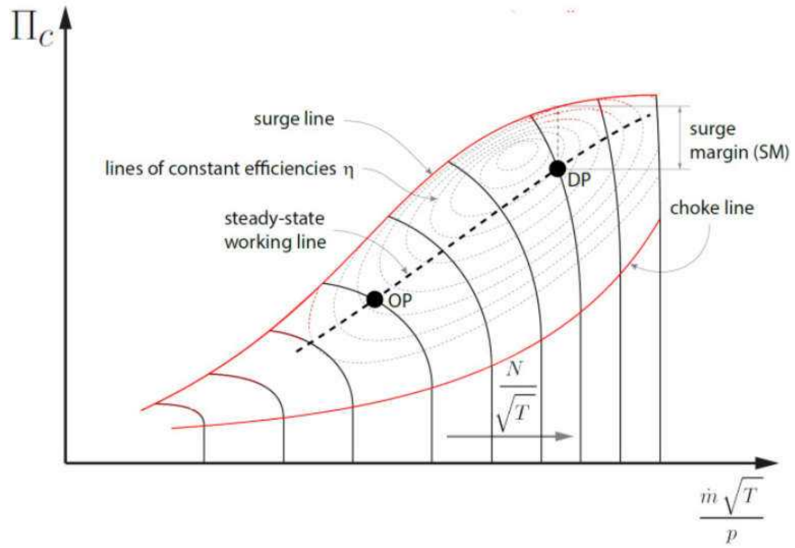

Figure 5: General compressor map representation [8]

Even in a stand-alone gas turbine, the compressor map is a relevant factor. In a hybrid power plant, the SOFC and various components (like pipes and valves) are inserted into the gas turbine cycle in between compressor and turbine. This implies that the pressure drop increases and load points move towards the surge line in the compressor map. Therefore, it is very relevant to analyse the compressor map itself, the surge line and the load points of the MGT test rig in the compressor map [10]. Even if all steady state load points are in stable conditions, the transients between the single points can lead into unstable conditions, like it was seen for different transient manoeuvers in Chapter 4.2. For example, within the commissioning and testing of the MGT test rig, it has been found that – depending on the speed of load changes – the system needs to be controlled very carefully to avoid running into surge. With the large volume of the vessel in between compressor and turbine, it even showed that the system runs into a constant back flow for some time in case the surge line is hit (Chapter 4.2.2, Figure 17).

In the scope of the project the power module was optimized as part of WP2. After successful implementation and testing in the standard MGT, the power module was also implemented in the MGT test rig. Therefore, the results below include two measurements of the turbo maps. The first generation of turbo maps was done on the standard stand-alone MGT before assembly of the MGT test rig using the initial power module, the second was done at the MGT test rig using the optimized component.

The maps for the compressor and the turbine have been characterized by measuring

- The standard operation line (operating points at different shaft speeds)
- Operating points with reduced back-pressure via opening the bleed air valve at different shaft speeds (see Figure 2)
- Operating points with increased back-pressure via closing the valve between compressor and recuperator at different shaft speeds (see Figure 2)

The compressor map and the turbine map for the optimized power module can be seen in Figure 6 and Figure 7.

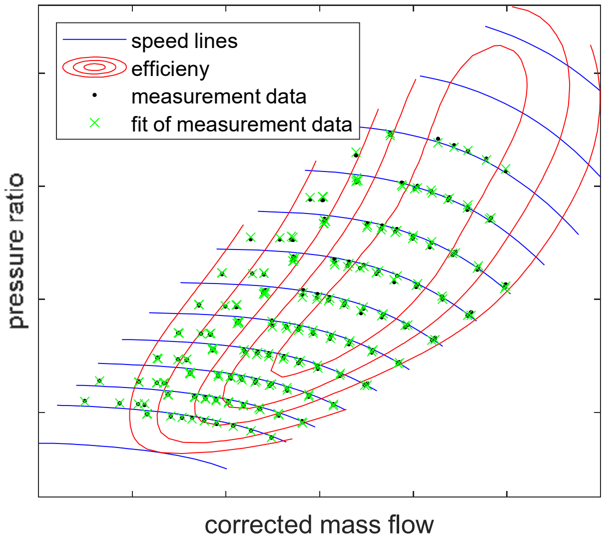

Figure 6: Compressor map of the optimized MGT compressor within the MGT system [9]

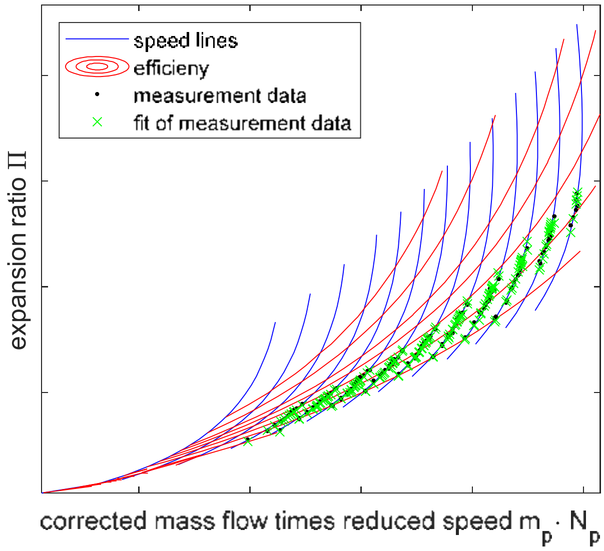

Figure 7: Turbine map of the optimized MGT turbine within the MGT system [9]

The maps have been generated by taking the measurement data (black dots) and fitting polynomials to them (a detailed description is given in Deliverable D1.7 [9]). In the compressor map, it can be seen that a wide operation area for different pressure losses in the system can be reached for each speed line. The operation range is limited for higher speeds. During the experiments with the optimized power module, only 220krpm could be reached in maximum. This is on the hand due to limitations in the power electronics, on the other hand it is due to the very low surge margin the steady state load points of the power module showed for speeds exceeding 220krpm implemented in the MGT hybrid power plant test rig. In contrast, for the old (none optimized) power module a maximum of 240krpm was feasible.

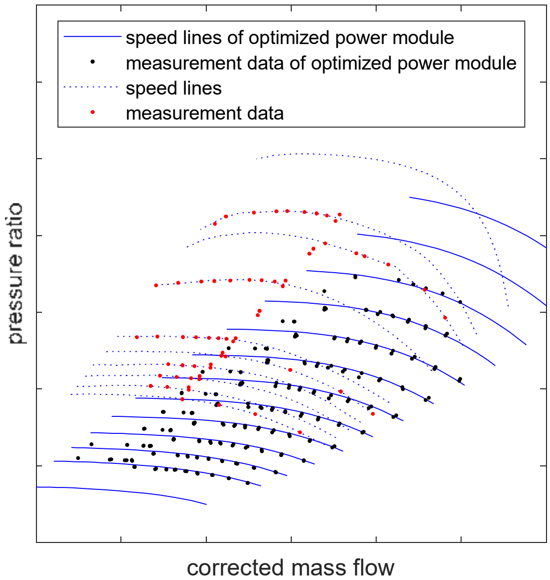

Figure 8: Compressor map: comparison of initial power module and optimized power module using measurement date of MGT and MGT test rig

In Figure 8 the results of the experiments done with the initial power module (dotted speed lines and red data points) and the optimized power module (straight speed lines and black data points) are drawn together in one graph. As mentioned already, in the old power module higher speeds have been reached. The difference in the lower speed lines is due to the fact that in the MGT the operation range is determined from 180krpm to 240krpm whereas in hybrid power plant operation it is necessary to extend the operation range to lower speeds and therefore lower air mass flows in the system. These low load points have been successfully tested for the optimized power module in the MGT test rig.

4.1.2 Combustion chamber

The combustion chamber is one of the key components connecting the fuel cell system with the turbomachinery. Due to the significantly different operating conditions compared to a standard natural gas operation, the combustor had to be designed specifically towards the hybrid system requirements ([11], [12]). This addresses mainly the very high inlet temperatures up to 850°C, the high amount of inert H_2O and CO_2 content in the fuel supply and hence the resulting very low heating value between approx. 1 and 3 MJ/kg for the SOFC off-gas.

To ensure stable operation over the expected operational range of the hybrid system, combustor investigations on the optically accessible atmospheric test rig were carried out before as presented in more detail in [13] and [14]. Different operating conditions, varying fuel cell temperature levels as well as simulated power output levels between minimal and maximal nominal system load and fuel composition (regarding biogas operation) were investigated.

As shown in Figure 9, successful operation with promising low emissions levels were achievable. However for low power operation, an artificial increase of the heating value by addition of natural gas directly to the combustor was necessary for stable operation. The reason for that are the excessively lowered combustion temperatures resulting from the high heat losses at the non-insulated atmospheric test rig. This effect is less pronounced in the pressurized machine combustion chamber configuration, which allows for a significantly better insulation.

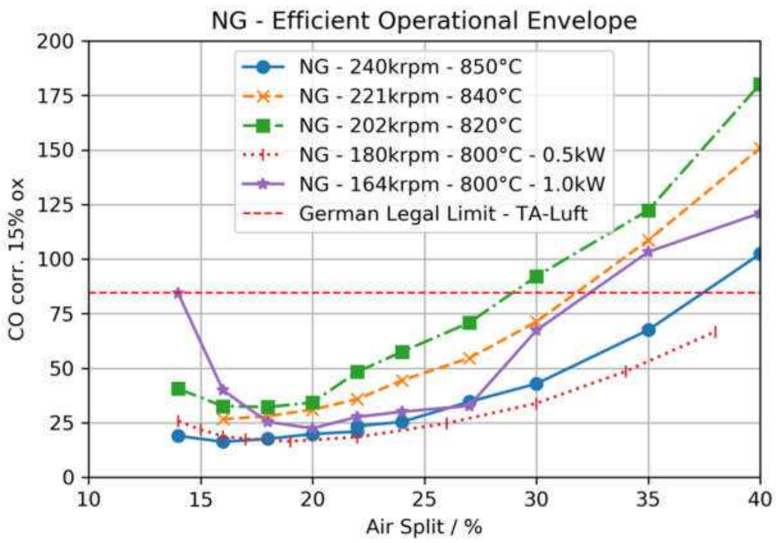

Figure 9: Operational range of the combustor covering different load levels allowing for an emission optimized choice of air split configuration [14]

As covered in [14], a biogas based operation of the system is possible with the developed combustion system. However the increasing difficulties towards low power operation due to further reduced resulting heating values and reduced overall system efficiencies caused by the required higher amounts of direct gas addition have to be accepted.

The combustion system for the pressurized machine test rig was derived from the atmospheric investigations. The design and setup of the system shown in Figure 10 is covered in [15].

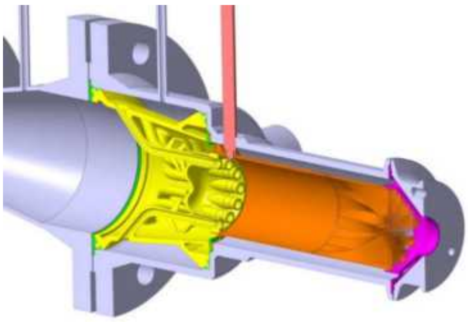

Figure 10: Overview of the machine configuration of the combustion system [15]

It has been manufactured and commissioned in the test rig and investigations showed a much wider stable operational range than under atmospheric conditions. This had been expected partly due to the highly reduced heat losses. Even the minimal power operation was possible without any stability issues or any additional fuel needed (see highlighted operating points, marked by stars, in previously unstable area in Figure 11).

Based on these results it is highly likely that the full operational envelope even for biogas mixtures with very low methane content is realizable. To determine the whole potential of the combustion system additional experiments are necessary.

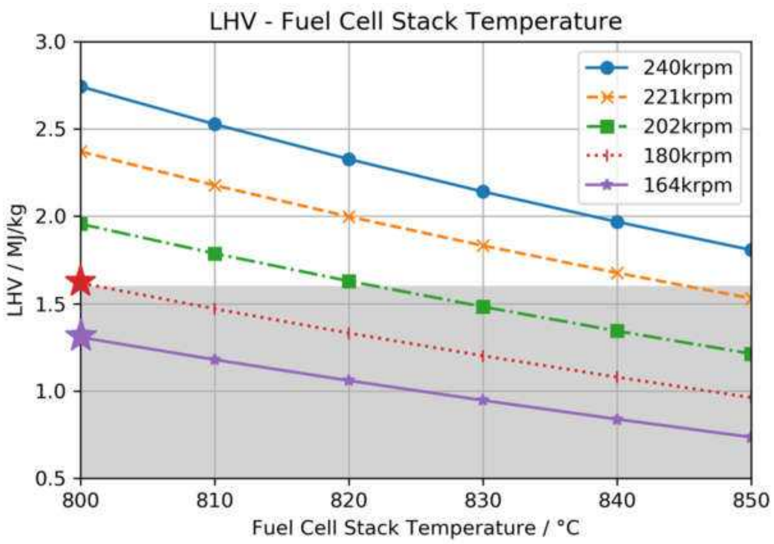

Figure 11: Lower heating value over fuel cell stack temperature for different shaft speed operating levels. Successful operation of the combustor marked with stars in region previously expected to be unstable (operation at atmospheric test rig impossible in grey shaded area) [14]

Regarding the start-up procedure of the hybrid system, some difficulties in igniting the combustion system at very low inlet temperatures were encountered. Without preheating to about 100°C a stable combustion was not achieved. This could be an issue for the start of the completely cooled down system bypassing the recuperator for the first start-up phase. One solution could be the integration of an electrical preheating device providing the heat necessary for the stable combustion in the first few minutes of operation. Another possibility is the addition of a stabilizing pilot stage to the combustor, which is highly recommended for future designs, since it would also improve the low power operation stability and possibly the emissions.

4.1.3 Recuperator

The recuperator is implemented in between the SOFC vessel and the fuel cell stack in the hybrid power plant cycle (see Figure 1). The allowed pressure difference between the outside of the SOFC and the inside, as well as between the cathode side and the anode side are limited. Therefore, the pressure drop of the air stream alongside the recuperator is a very relevant factor, as this pressure drop adds directly to the pressure difference between the outside of the SOFC and the cathode side inside the SOFC.

The original recuperator showed a pressure drop of the air side around 50mbar – depending on the load point. As the SOFC could not withstand this pressure drop according to supplier information, the recuperator had to be changed in its design and re-manufactured to have a far lower pressure drop in the range of approximately 10 to 20mbar. The optimization within the recuperator applies to many recuperator-internal components such as cells, nozzles, tubes and manifolds and has been reported in Deliverable D2.8 [16] of this project. The optimized recuperator is shown in Figure 12.

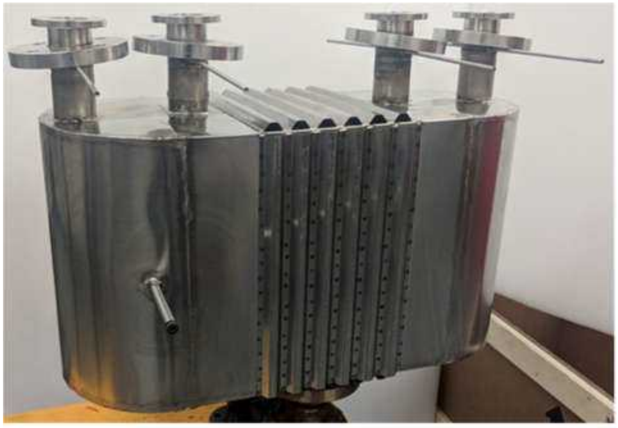

Figure 12: Newly manufactured recuperator [2]

Analysis of the experimental data gained on the MGT test rig showed the following: The measured pressure drop, the pressure difference of the air before and after the recuperator, shows very small and mostly even negative values. Physically this is not possible. Yet, the measurement accuracy of the pressure sensors is around 10mbar each. Therefore, the pressure drop can't be determined accurately, but it can be said that it is below 20mbar (equal the double measurement accuracy) and therefore the optimization limit is reached. This can be seen in Figure 13: It shows the difference between the measured pressure at the inlet and the outlet of the air side of the recuperator.

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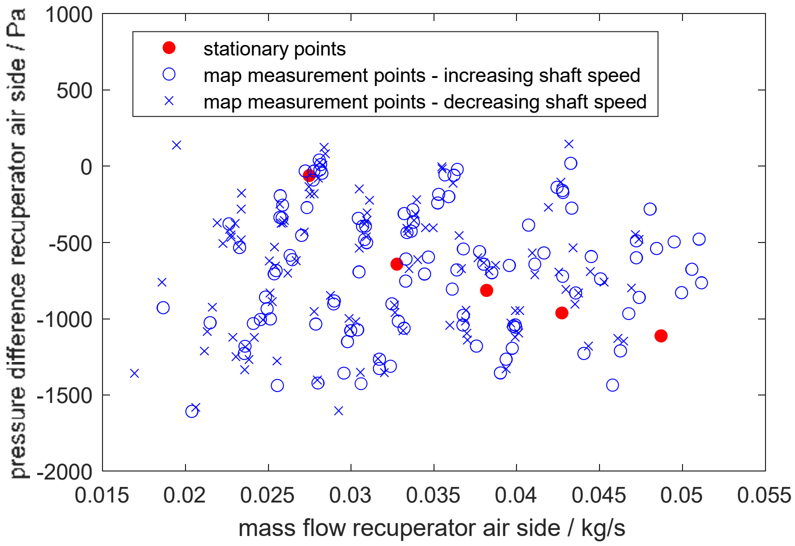

Figure 13: Difference between measured pressure at inlet and outlet of air side of recuperator [9]

Shown are the available measurement points of static points of the system as well as the points which are measured during the turbomachinery map creation. For these points the system is not heated through completely, however, the air flow is showing steady state conditions. It is assumed that the pressure losses can be assumed as stationary. This assumption is supported by the fact that in Figure 13 points of increasing and decreasing shaft speeds and therefore increasing and decreasing temperature levels are not divided into two separated groups. Figure 13 shows that the difference of the measured pressure at the recuperator scatters arbitrarily and thus the expected correlations are hidden by the uncertainty of measurement.

Nevertheless, the pressure drop analysis shows that this version of the recuperator fulfils the requirements for integration into a real coupled hybrid power plant.

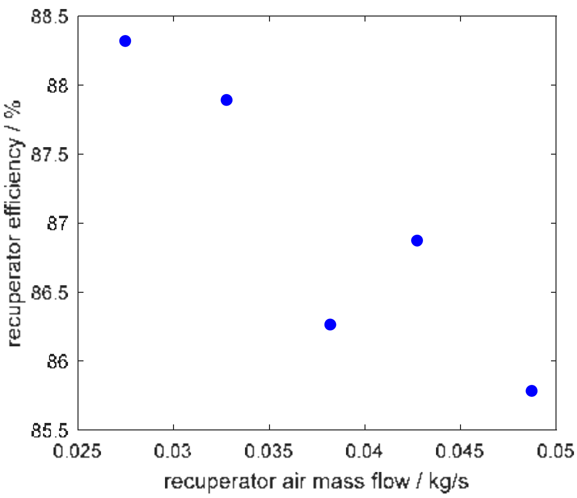

Figure 14: Efficiency of the recuperator [9]

Figure 14 shows the efficiency and the heat losses over the air mass flow, calculated from the steady state measurement data. To compute the efficiency, the quotient of enthalpy difference and maximum possible enthalpy difference is calculated for both sides individually. The efficiency is the maximum of both quotients [17]. The third measurement point with an air mass flow of about 38 g/s seems to have a different behaviour than the other steady state points. This is, because accidentally the vessel emulator heater was out of order during measurement of that load point and therefore, the air inlet temperature of the recuperator for this state was significantly lower than for the other load points [9].

It has been found that the heat losses in the MGT system do have a significant impact onto the recuperator efficiency and influence as well the recuperator inlet temperature. These findings and the conclusions are reported in [9] within the validation of models.

4.2 Transient characteristics

For the set-up of a control strategy for a hybrid power plant the transient manoeuvers of the two subsystems MGT and SOFC have to be analysed and adapted in a way to include all boundary conditions and limitations of both subsystems to guarantee a safe and reliable operation of the combined system.

A feasible way to start and heat up the system had to be found. Changes of the demanded electrical system load had to be responded to and the system needed a procedure to be stopped safely. Additionally, an accelerated emergency stop manoeuvre had to be defined and tested as a reaction to unexpected system behaviour. Critical events have to be investigated and limitations have to be defined to avoid operation in those areas.

4.2.1 Start-up procedure

An SOFC has to be preheated close to the operating temperature to start the electrochemical reaction. Therefore, the MGT has to be started first and is used to heat up the fuel cell stack very gently with very slow temperature gradients. For realising a slowly increasing temperature profile, a possibility to bypass the recuperator is needed to prevent sudden temperature rise in the air feed to the fuel cell (see Figure 1). This procedure combined with the relatively high thermal capacity of the system leads to a combustion chamber ignition process with absolutely cold air supply at ambient temperature level. Despite the promising successful ignition tests at the atmospheric test rig, the combustion chamber in the machine environment shows combustion instabilities under these conditions (see 4.1.2). For the start-up of an SOFC it is necessary to flush the anode side with forming gas – a mixture of nitrogen and a small content of hydrogen (5 up to 10%). Further investigations with realistic forming gas contents in the gas supply have to be carried out to understand the problem in more detail. Since the resulting H_2 content could potentially improve the conditions enough for a successful start-up cycle. This circumstance has to be payed closer attention for future work.

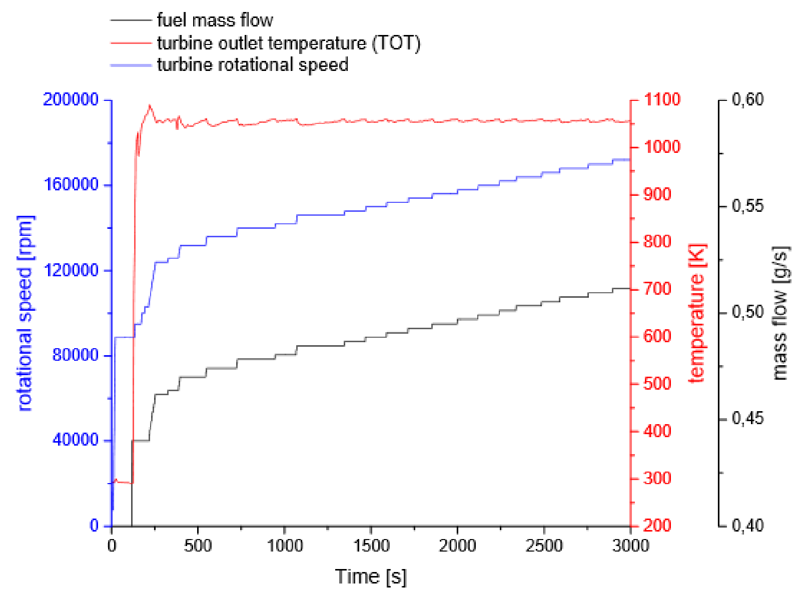

Figure 15: Automatic start-up procedure of the MGT system with a natural gas combustor [4]

Compared to the test operation of the system with a standard natural gas combustor, the start-up procedure had to be adjusted. In first attempts to rebuild the original manoeuvre in the MGT test rig (see Figure 15), the TOT was raised very quickly towards the target value of 1060 K. This procedure leads to the highest achievable efficiency during heat up of the system but comes with a significantly increased fuel flow and resulting reduced air to fuel ratio (lambda) in the core combustor. The off-gas combustor was designed for steady-state hybrid conditions, leading to a much lower air split (the ratio of air fed to the core combustor divided by the total airflow including dilution air). However, the increased fuel supply led to fuel rich conditions with incomplete combustion occurring without even reaching the target TOT. Consequently, the manoeuvre was improved by controlling the fuel supply via keeping up a constant target air to fuel ratio. This leads to a slow increase of the TOT but also a cleaner and more stable combustion during heat-up as shown in Figure 16. For the hybrid system, the resulting delay in temperature increase is accommodating the temperature gradient limits of the fuel cell.

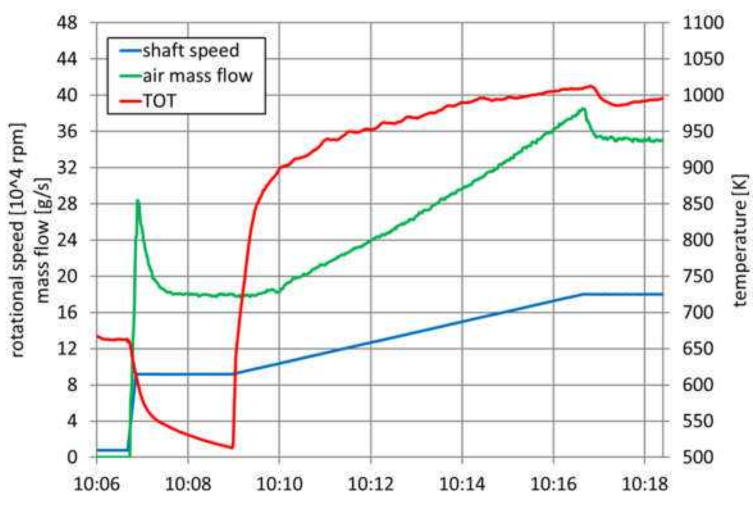

Figure 16: Improved start-up procedure with constant air-fuel ratio and slow TOT increase

In general, the start-up procedure has to be realized with significantly lower rpm ramps than with the standard MGT. As described in more detail in the next chapter, the correlation between changes in pressure and mass flow within the test rig is a very slowly reacting system which leads to specific difficulties for fast changes in rotational speed. Despite the slow ramp up speed the resulting overshoot spike in mass flow due to very slowly reacting pressure conditions described in the next chapter is already obvious in Figure 16 when reaching ignition speed and target speed.

4.2.2 Load Changes of the MGT

A load change of the hybrid system typically consists of a load change at the fuel cell system coupled to an adaption of the rotor rotational speed to compensate for the resulting change in the boundary conditions in terms of operating temperature level and needed air mass flow. In a typical standard configuration of an MGT system with a relatively small pressurized volume, these changes in rotational speed can be performed quite fast. However, with a system like the hybrid power plant, the pressurized volume is inevitably increased significantly due to the integrated fuel cell system in between compressor and turbine. This leads to unusual transient system behaviour in terms of mass flow and pressure build up or drop. Both parameters are not connected directly with a fast response any more but are coupled with quite large delay times.

Especially the load changes towards lower power settings with decreasing rpm ramps become a critical manoeuvre since the pressure is retained temporarily while the mass flow drops very quickly as illustrated in Figure 17. This leads to a transient compressor behaviour approaching or even exceeding the surge limit (surge line) quite easily which was impossible with the standard MGT. Figure 17 shows the strong influence of the internal buffer volume comparing the two mass flows before and behind the vessel simulator following a typical load change. The critical situation occurs because of the fast decreasing mass flow at the compressor (orange line) with a very slowly responding pressure drop (dashed black line), pushing the operating point in the compressor map temporarily far left close to the surge limit.

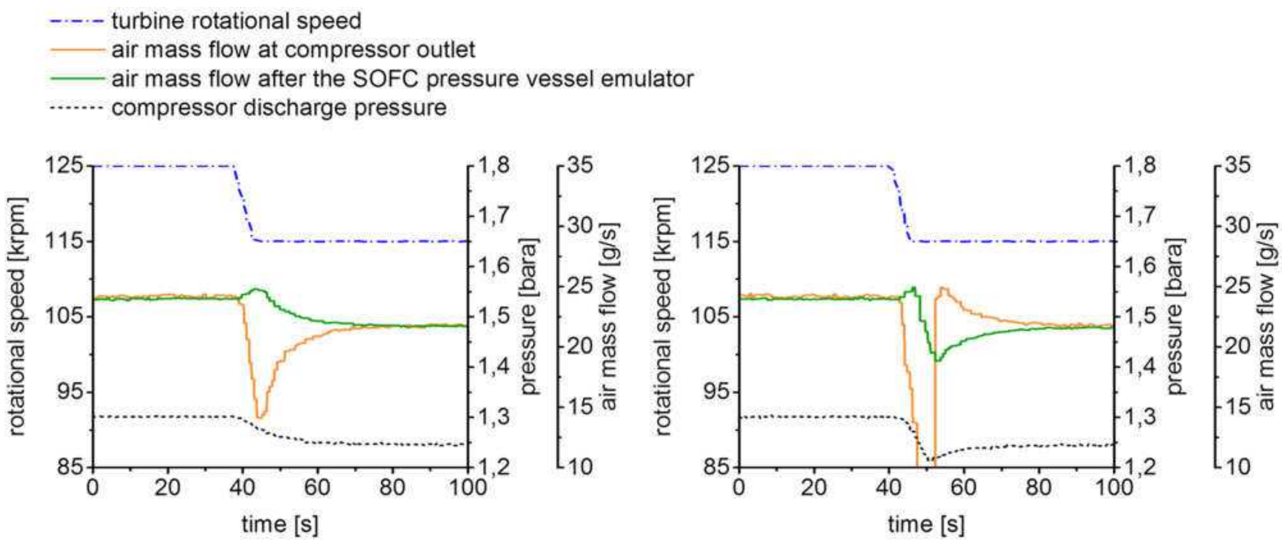

Figure 17: Pressure and mass flow behaviour with a load change towards lower rotational speed (on the left save manoeuver, on the right manoeuver leading to a constant backflow at the compressor)

4.2.3 Critical events

Developments of the compressor rotor towards better performance (in terms of efficiency) led to a more critical surge behaviour than before, not important for the standalone system, but drastically impacting the hybrid system. Switching to a more advanced compressor component, it was not possible any more to reach maximum rotational speeds without causing a compressor stall with constant backflow or even cyclic compressor surges (see Figure 18), observed for the first time for this machine at all. A maximum rotational speed limitation at 220krpm had to be implemented to prevent this from happening.

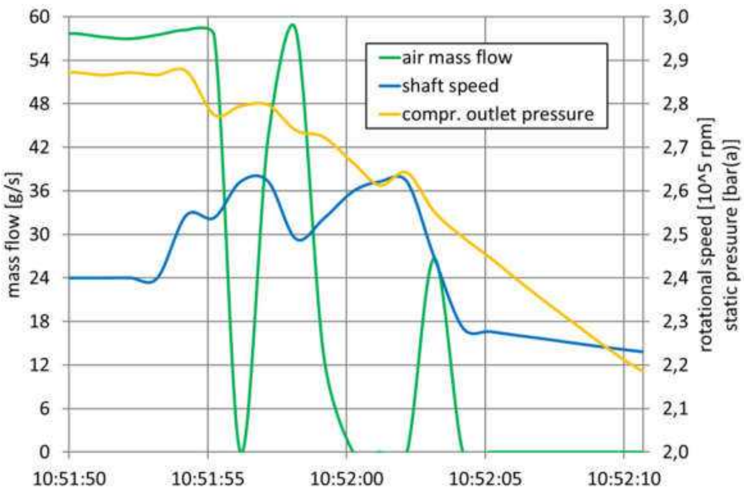

Figure 18: Cyclic compressor surge event with resulting over-speed

4.2.4 Shutdown procedure

For shutting down the hybrid system, the electrochemical reaction in the SOFC has to be stopped first. Afterwards, the system has to be cooled down gently with a very slow temperature gradient (of about 5K/min) while the anode has to be flushed with reforming gas. To adjust a defined temperature profile at the inlet of the SOFC cathode side, a combination of air from the recuperator bypass path and recuperator path is used (see Figure 3) and mixed in front of the SOFC. When reaching a target temperature level, the gas turbine can be stopped. Since the pressure level inside the whole system and also the amount of available air flow to the fuel cell depend on the rotational speed of the gas turbine, this process has to be performed in a slow and controlled way.

The described load change behaviour (see Chapter 4.2.2) has a strong impact on the feasible shutdown procedure. The surge problems connected with a deceleration of the turbomachinery shaft require a very gentle and slow reduction of the rotational speed especially at high rpm levels. As a result, with the limitations of the turbo components alone, without taking into account temperature and pressure gradient limitations of the fuel cell system, the nominal shutdown of the test rig requires several minutes of ramp down time before even cutting off the fuel supply. To prevent electrical generator overload scenarios in cold conditions of the system, the fuel supply is cut off at a much lower rotational speed than before. The flame, and hence thermal power input into the system, is kept running until reaching a shaft speed of 120krpm (see Figure 19) instead of cutting off fuel at 180krpm like the standard system does.

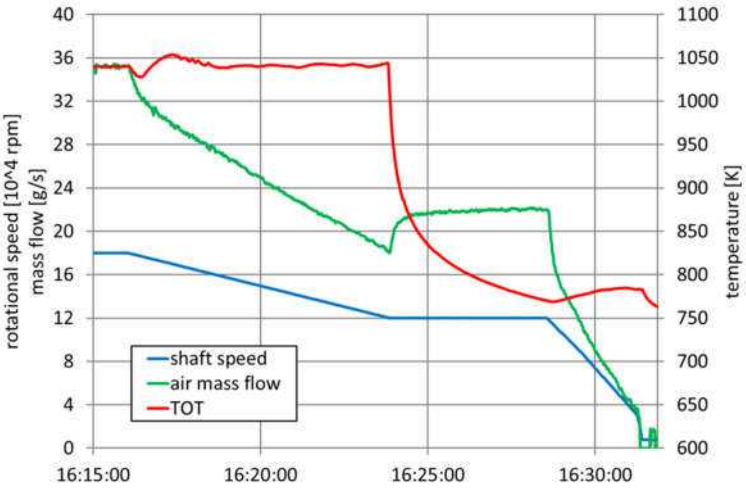

Figure 19: Extended shutdown manoeuvre: with reduced turbine speed using the electrical motor

4.2.5 Emergency procedures

In an emergency scenario the priority is a safe and fast stop of the system avoiding any harm to people. Hence, a fast shutdown with an immediate stop of the fuel supply is triggered by the independent TÜV-certified high level safety PLC. All fuel supplies are shut down immediately and the target is to get the shaft to a stop as fast as possible while preventing unnecessary damage to the components at the same time. The manoeuvre is shown in Figure 20. In this case a backflow over the compressor is accepted and kept intentionally down to a safe rpm level to prevent the generator from overloading electrically in the moment of re-stabilisation of the flow. This overload would lead to a loss of generator breaking force and trigger a completely uncontrolled free-running spin-up of the shaft. The bleed air valve is opened partially to decrease the system pressure more quickly allowing for a faster ramp-down. The emergency stop manoeuvre implemented runs completely autonomous when triggered without any user input required and brings the system to a complete stop safely.

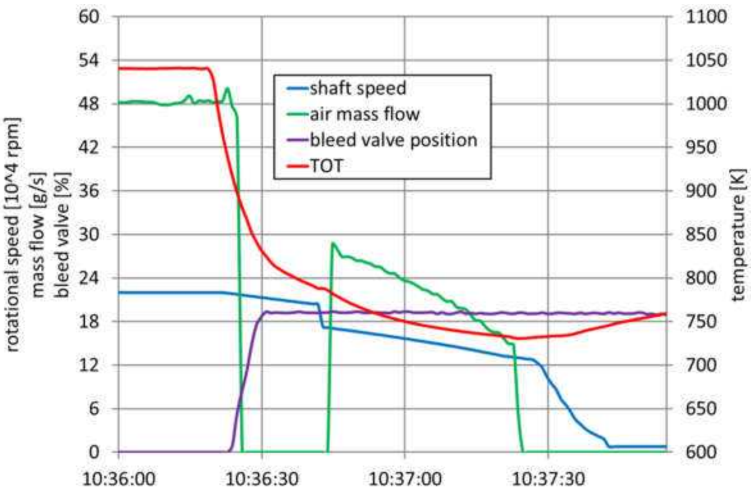

Figure 20: Emergency stop manoeuvre with partly controlled backflow through the compressor

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5 Conclusion

In the scope of the Bio-Hypp project a MGT hybrid power plant test rig has been set-up, commissioned and characterized. The test rig is based on a real MGT with emulation of the SOFC.

For the analysis of the steady state load points a focus was set on the components compressor, combustion chamber and recuperator. These components imply the strongest boundary conditions onto the whole system. The compressor map has been generated and analysed as it defines the stable operation range for the hybrid power plant. It was seen that the optimization of the compressor to reach higher efficiencies limits the operation range for the use in a hybrid power plant for higher turbine rotational speeds. The components recuperator and combustion chamber have been optimized as they are crucial for the operation of a hybrid power plant. As the recuperator is implemented in between the SOFC pressure vessel and the stack itself, special attention has to be set on the pressure loss. In addition, the efficiency of the recuperator influences the inlet temperature to the SOFC. With the optimized recuperator the pressure drop target could be achieved. The combustor is the most important coupling device as it has to start-up the system, heat up the SOFC and use the SOFC off-gases during operation. The newly developed SOFC off-gas combustion chamber was successfully commissioned in the pressurized test rig and showed stable operation with natural gas. Different emulated hybrid operating points were investigated using the successfully adapted hot steam generator for off-gas emulation. The expectations from the previously carried out investigations on the atmospheric test rig regarding stability were exceeded and a stable operation without any additional fuel was possible in the most critical operating points of the target range.

The transient characteristics have been adapted stepwise to guarantee a safe control of the system avoiding critical conditions. At first the manoeuvers start-up, load change and shutdown were derived from the standard MGT manoeuvers and tested at the MGT test rig. After integration of optimized components the procedures have been adapted to meet the boundary conditions of the new components and the SOFC system. A feasible start-up procedure was found and automated considering the challenges found regarding load changes and mixture control. Possible shaft speed gradients were investigated and a suitable shutdown manoeuvre was derived. For emergency situations, a procedure was developed, allowing the inevitable compressor surge, to happen in a controlled way and re-stabilising the flow at a safe level of rotational speed to prevent electrical damage in the generator inverter unit.

The analysis and findings about the system behaviour and the characterizations of the components have been used to revise the concept for the real coupled hybrid power plant demonstrator. It was seen that some components of the system like the combustion chamber need additional improvement. The procedures for start-up, load change and shutdown could be successfully adapted to the requirements in a hybrid power plant.

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