Grant No.: 641073

Bio-HyPP

Deliverable No	**Title**	**Submission Due Date**	**WP/Lead**
D4.6	Hybrid power plant - Concept for coupling MGT and SOFC	31.12.2019	WP4 / DLR

Short Summary	This deliverable was originally planned to show the technology demonstrator having operated for 100 hours. The technology demonstrator could not be built within the project frame, as insights on the two separate test rigs (MGT test rig and SOFC test rig) necessitate changes on components and the coupling concept. Therefore, this report describes the revised concept for coupling MGT and SOFC.
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Printed Date	26.02.2020

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Table of Contents

List of Figures

List of Tables

List of Acronyms

El	electric
FLOX®	flameless oxidation
MGT	Micro gas turbine
MGT test rig	Hybrid power plant test rig consisting of real MGT and emulated SOFC
MPC	Model predictive control
MTT	Micro Turbine Technology B.V
Ref	Reformer
Rpm	rounds per minute
SOFC	Solid Oxide Fuel Cell
SOFC test rig	Hybrid power plant test rig consisting of real SOFC and emulated MGT
WP	Work package

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. Therefore, two separate test rigs have been set up for the characterization of both subsystems under hybrid conditions, as a part of WP4: the MGT hybrid power plant test rig (real MGT with emulated SOFC) [2] and the SOFC hybrid power plant test rig (real SOFC with emulated MGT), ([3], [4]).

In the beginning of the project, the aim was to build a technology demonstrator of a real coupled hybrid power plant consisting of MGT and SOFC. This deliverable was originally planned to describe the operation of the technology demonstrator of the hybrid power plant of MGT and SOFC.

In the course of the project, various issues occurred with components and their interactions while setting-up and while running experiments with the separate test rigs MGT hybrid power plant test rig and SOFC hybrid power plant test rig. These issues on the one hand cost a lot of extra resources (time and manpower). Therefore, the experiments on both the separate test rigs had to be extended to cope with the occurred issues: a surge and backflow-issue at the MGT hybrid power plant test rig destroying the engine had to be solved [5], control issues had to be fixed and the layout of the SOFC hybrid power plant test rig had to be revised. On the other hand, auxiliary components being standard products procured from the market - such as electronic load and the recirculation blower- failed iteratively and caused delays with the experimental results that had not been planned. It has been found that the components and also the auxiliary components need to be characterised even more deeply to be taken into account for the real coupling.

So, the assumption that the set-up of two separate emulation test rigs and their experimental characterisation is needed as one step before coupling has been proven to be essential.

Due to these reasons the technology demonstrator could not be built within the project frame and the focus has been moved towards separate test rig characterization, their components and interactions. This has led to the insight that the coupling concept needs some conceptual changes to allow for real coupling.

This report of D4.6 describes now the revised concept for coupling MGT and SOFC into one hybrid power plant. It is subdivided into five chapters.

Chapter 2 describes the objectives of the deliverable.

In chapter 3, the two main subsystems MGT and SOFC the hybrid power plant demonstrator is based on are briefly introduced.

Chapter 4 describes the revised plant layout, the control system, the components of the hybrid power plant and modifications needed. These are based on the insights and experiences gained with the two separate test rigs ([16],[5]).

Finally, Chapter 5 draws the conclusions.

2 Objectives and requirements

The objective of this report is to provide a concept for the real coupling of a hybrid power plant consisting of the components MTT EnerTwin MGT and Sunfire SOFC [1]. The characteristics of the chosen components influence the plant layout and the control concept highly. Therefore, the objective is to provide a concept that works with the chosen components.

The concept needs to take into account:

- High electrical efficiency
- Operational flexibility
- Operational area
- Control concept of the power plant including start-up, load changes, ramp-down and emergency manoeuvres

Based on the initial concept and on the experiences and insights gained with the separate test rigs ([2],[3],[4],[16]), the new concept is adapted to the chosen components and introduced in the following chapters. In addition, modifications of components needed for reaching the specified goals are discussed.

3 Components for setting-up a hybrid power plant demonstrator

3.1 MGT system: MTT EnerTwin

The MGT EnerTwin from MTT (picture in Figure 1) has an electrical power output of 3kW in its original version. It is a single shaft, recuperated micro gas turbine with a maximum pressure ratio of 3. In base load the turbine speed is 240000 rpm and the air mass flow is approximately 0.056 kg/s. The micro gas turbine system offers a very high recuperator outlet temperature of approximately 730 °C. Using the exhaust gas heat exchanger a thermal power output of approximately 14.4 kW can be reached. The main characteristics are summarized below in Table 1.

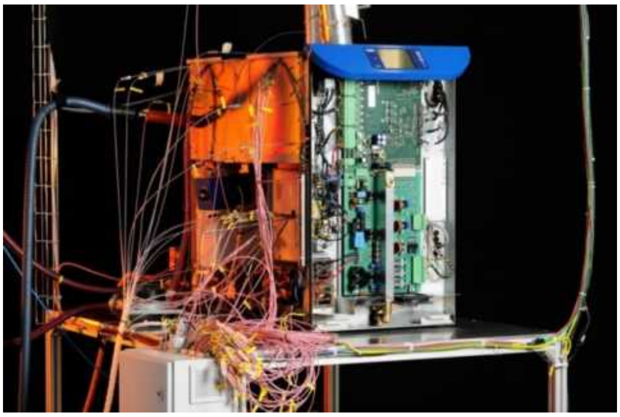

Figure 1: MTT EnerTwin with detailed instrumentation at DLR

Characteristics	
El. power output	3 kW
Thermal power output	14.4 kW
Pressure ratio	3
Max. turbine speed	240000 rpm
Air mass flow	0.056 kg/s
Recuperator	yes
Recuperator outlet temperature	730 °C
Exhaust gas heat exchanger	yes
Bearing system	Oil bearings

Table 1: Characteristics of the MGT MTT EnerTwin

Figure 2 shows the process diagram of the EnerTwin micro gas turbine consisting of compressor, turbine, generator, combustion chamber, recuperator and exhaust gas heat exchanger.

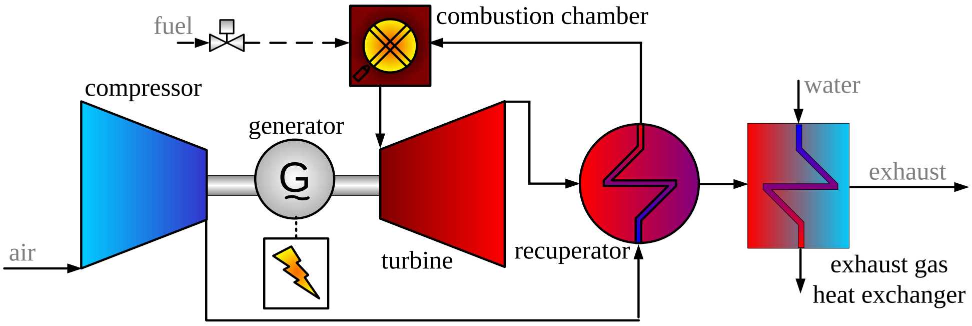

Figure 2: process diagram of the EnerTwin MGT

The main advantages of using a MTT EnerTwin MGT for a hybrid power plant demonstrator are:

- Flexible set-up that allows the integration of the SOFC components
- Reasonable power output and size to build a lab scale hybrid power plant demonstrator
- High recuperator outlet temperatures (resulting in high inlet temperatures to the SOFC)
- Surge margin sufficient for hybrid power plant application

3.2 SOFC system: Sunfire

The chosen SOFC is a planar, electrolyte supported SOFC from Sunfire with an electrical power output of 30 kW. The SOFC is composed of 6 sub-modules with 240 cells each. For the operation in a pressure vessel the compression system was newly configured for a temperature of up to 400 °C and an encapsulated sensor area was developed. Figure 3 shows a picture of the SOFC stack without auxiliary components and pressure vessel. Table 2 summarizes the characteristics of the SOFC.

Figure 3: Sunfire SOFC with instrumentation at DLR

Characteristics	
El. power output	30 kW
Type	Electrolyte supported
Electrical efficiency (LHV)	60 %
Operation temperatures	800 – 850 °C
Minimum anode inlet temperature	650 °C

Table 2: Characteristics of the Sunfire SOFC

Figure 4 shows the process diagram of the SOFC system. For the operation with natural gas from the grid, the SOFC has to be equipped with a desulphurization. For the reforming of natural gas a catalytic steam reformer (Ref) was implemented. Water and heat for the reforming reaction within the reformer were supplied by the recirculation of hot anode off-gas in a recirculation cycle. In addition, the incoming fuel was preheated by it. The recirculation is driven by a flexible, high temperature blower. For the pressurization operation the SOFC, recirculation blower and steam reformer are implemented in a pressure vessel. At the exhaust gas outlet a catalytic burner was used to deal with the exceed fuel. For the emulation of the compressor of the MGT a compressor simulator is implemented, while the pressure increase was controlled via a main valve in the catalytic burner component. For the recuperator of the MGT system a heat exchanger with a parallel hot bypass valve was used. The recuperated heat was simulated via a natural gas burner. For cooling purposes of the sensor compartment below the SOFC additional air was supplied. The pressure was controlled via an additional valve.

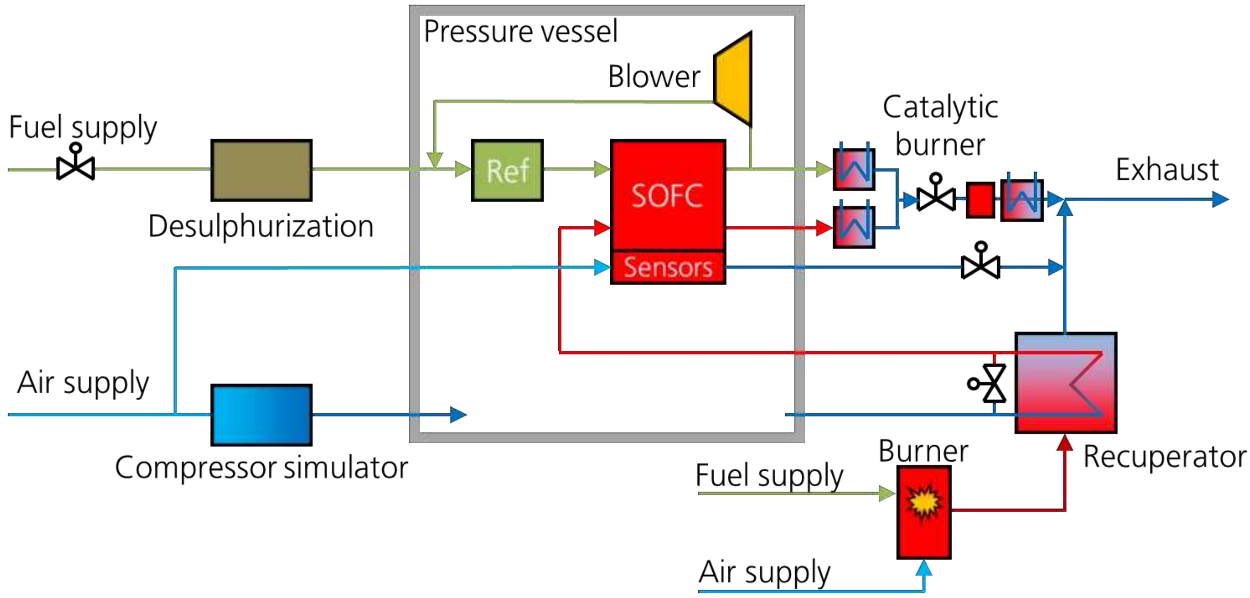

Figure 4: process diagram of the SOFC system

The main advantages of using a Sunfire SOFC for a hybrid power plant demonstrator are:

- Electrolyte supported cells offer a higher mechanical stability than anode supported cells, which is an advantage for pressurized operation with the risk of pressure fluctuations.
- Sunfire offers with the modular system a size in electrical power output that is suitable for coupling with the MTT EnerTwin MGT (power ratio SOFC:MGT is 10:1).
- SOFCs show positive effects to pressurization. With increasing pressure the driving force in terms of voltage increases and diffusion losses decrease, thereby increasing the efficiency. Especially the last effect is significant for anode supported cells but less important in electrolyte supported ones that were used.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 641073

4 Concept for a hybrid power plant

Based on the chosen subsystems for the MGT and the SOFC and on numerical simulations, the cycle layout for a hybrid power plant was developed [1]. Therefrom the layout for the two separate test rigs was derived [2],[3],[4]. With the two test rigs the concept could be validated and necessary changes to the concept and the components were derived. The experimental tests showed the need of improvements for single components and the control concept. In addition it was found that the heat losses play a major role for the operation range and the feasibility of a hybrid power plant in general.

In the following chapters the adapted concept is shown and some further necessary modifications are discussed.

4.1 Hybrid power plant layout

Figure 5 shows the cycle layout for the hybrid power plant demonstrator. The air is compressed in the compressor of the gas turbine and then fed into the pressure vessel surrounding the SOFC system. This is done to achieve nearly the same pressure that surrounds the SOFC and inside of it. In addition, the vessel is purged. The air is then preheated in the MGT recuperator and led into the cathode side of the SOFC. Fuel is first desulphurized and then reformed. The recirculation blower recirculates part of the anode exhaust gas to provide the water content and heat needed for the reforming reaction and to preheat the incoming fuel. The fuel is then led to the anode side of the SOFC and electrochemically oxidized, while supplying electrical power. The exhaust gases of anode and cathode are fed separately to the combustion chamber. In the combustion chamber, the SOFC off-gas is burned. The hot exhaust gases are expanded in the turbine, cooled in the recuperator and leave the cycle through an exhaust gas heat exchanger (not shown in the cycle layout).

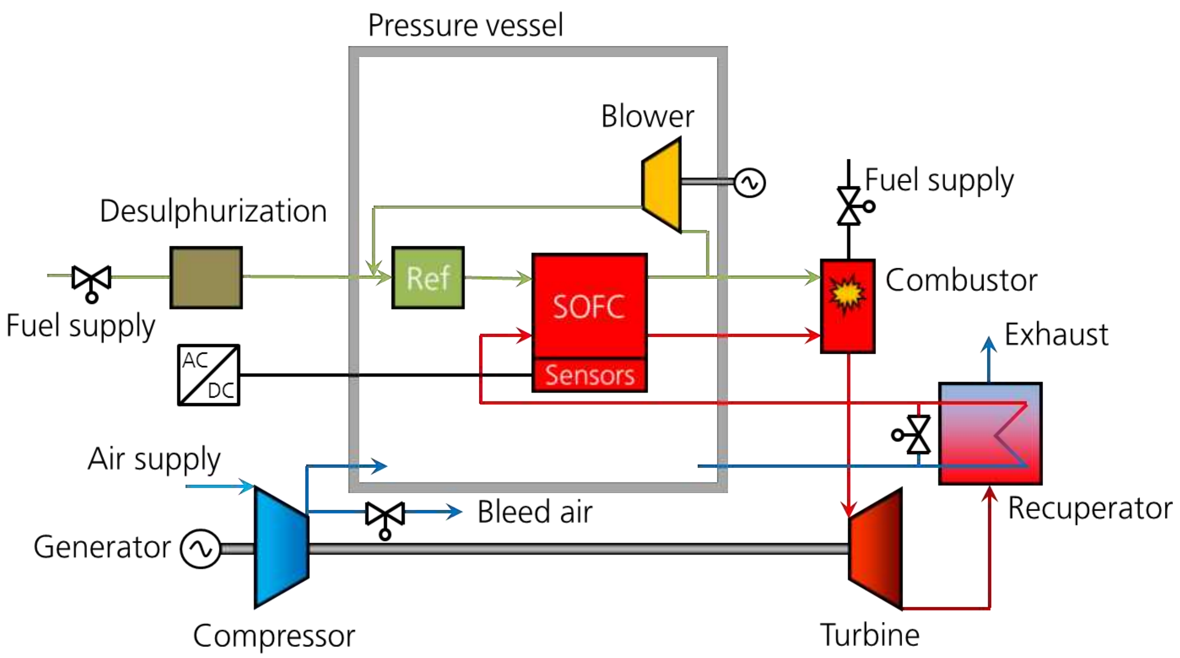

Figure 5: Hybrid power plant layout

For the system start-up an additional path is implemented bypassing the recuperator. Herewith, the inlet temperature of the SOFC can be adjusted by using a hot temperature valve. For emergency manoeuvers a bleed air path is implemented at the outlet of the compressor.

The results of the experimental investigations with the separate test rigs show that only slight changes to the overall layout are necessary:

1. The arrangement of the components should allow for minimal length of piping system to minimize heat losses.
2. It was recognized that the heat supplied by the recirculation of the anode off-gas was not high enough to reach the needed temperatures at the anode inlet of the SOFC while reforming fuels with high concentrations of natural gas, mixed with hydrogen. An additional heat exchanger that utilizes heat of the anode or cathode outlet would help to optimize heat integration.

The layout is suitable for the hybrid power plant demonstrator but demands some constraints the single components have to comply:

1. The SOFC and its housing have to deal with a slightly higher pressure surrounding the SOFC in the pressure vessel than inside the cathode and anode side. The housing has to withstand this pressure difference even under operation temperature.
2. The heat insulation has to be improved.
3. As mentioned before, the arrangement of the components has to be improved to minimize the length of the piping system and therefore minimize heat losses and pressure loss.

4.2 Concept for the control system

The foreseen control system is based on PID controllers. The use of PID controllers is much simpler than other types of controllers, for example model predictive control (MPC), and is well known. It was assumed that in a first step, the system does not need the capability for highly transient changes and all changes are done smoothly. For that PID controllers were stated to be robust enough to be used in the system.

The investigations at the separated test rigs showed that there is a need for at least feed forward controllers in some control loops. Therefore the control system had to be optimized in a first step with feed forward controls. In a second step it may need to be enhanced even further for load following transients and to reach higher operational flexibility.

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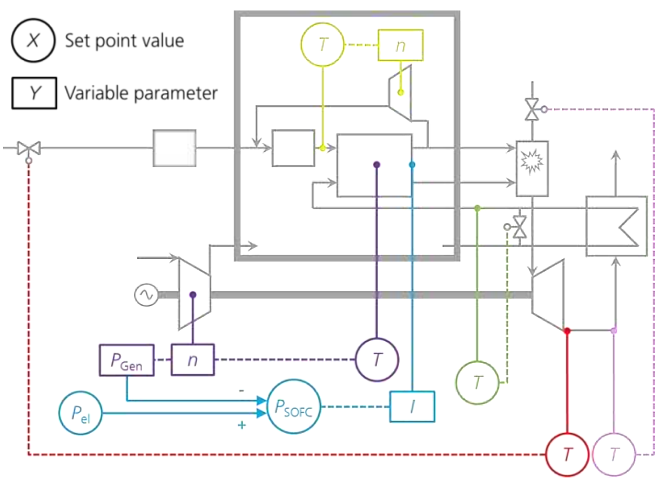

Figure 6: Overview of control loops for the hybrid power plant demonstrator [17]

	Control loops
	Control of recirculation blower speed for adjusting temperature at SOFC anode inlet
	Control of TOT and monitoring of max. recuperator inlet temperature
	Control of TOT for start-up and shutdown without SOFC operation
	Air mass flow control for monitoring SOFC core temperature
	Control of overall electric power demand composed of MGT and SOFC power
	Valve control for monitoring cathode inlet temperature for start-up and shutdown

Table 3: Control loops

Figure 6 and Table 3 summarize the foreseen control loops for a hybrid power plant. The safety control is not shown in this overview. The safety control composed of plant safety and personal safety of the two separated test rigs has to be combined for the control system of the demonstrator. The safety control of the test rigs has been tested and optimized during the tests.

The plant safety contains the monitoring of all relevant parameters to prevent damage of the facility like the surveillance of temperatures, pressures, gas flows, voltages, el. currents, gas leakages, rotation speeds, media supply, el. grid and control hardware errors. The control system contains a list of critical measuring values with preconditions and reacts with a predefined manoeuver. The personal safety system is overriding the plant safety and prevents of harmful events for people around the power plant.

4.3 Components

The main subsystems MGT and SOFC have to be adapted for the integration into a real coupled hybrid power plant demonstrator. Especially the set-up of the MGT has to be changed completely for the integration of the SOFC. For some components, like recuperator, combustor and MGT power module the adaption or even redevelopment was already foreseen in the scope of the project plan. During experiments, using the separated test rigs, the necessity for further adaptions has been seen.

4.3.1 Power module

The MGT power module is composed of the compressor, the turbine and the generator mounted on one shaft including bearings. Figure 7 shows a photo of the EnerTwin power module.

Figure 7: Photo of the EnerTwin power module [7]

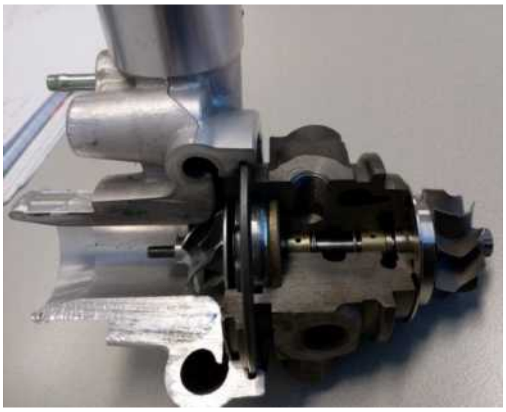

Figure 8: Photo of the insights of the power module [7]

4.3.1.1 Bearings

The original MGT uses oil bearings (see Figure 8). Using oil bearings, there is always a small amount of oil injected into the air stream in the compressor. This is caused by the sealing concept of the oil bearings: the compressed air serves to seal the oil bearings by the air pressure. In the moment of starting or stopping the system the oil pressure is momentarily higher than the air pressure and therefore small oil quantities are injected into the air stream.

The oil often contains sulphur and is therefore critical for the SOFC. The risk of sulphur poisoning the SOFC cathode side from the air cannot be eliminated. One solution to get rid of the oil is to use different bearings, for example air bearings. In the project it was already planned to develop air bearings for the MGT EnerTwin, but couldn't be fulfilled in the scope of the project period. It has been found that for a hybrid power plant air bearings are mandatory.

4.3.1.2 Compressor and turbine

The turbo-components for a hybrid power plant have to be very robust as the SOFC integrated in the micro gas turbine cycle and increases pressure loss significantly, changes retention time and temperatures in between compressor and turbine. The compressor is limited by the so called surge line [5]. A stable operation across this line is not possible. Passing the surge line leads to compressor surge – a short flow reversal leading to high pressure fluctuations in the whole system. The experiments showed that there is also the possibility of constant backflow with this compressor as the volume of the vessel and the piping system in between compressor and turbine is very high. This would cause damages at both systems. The SOFC material could break and on the MGT side this leads to overcurrent in the generator resulting in an emergency shutdown and a damage of the bearings. Therefore, the compressor's most important characteristic is to show a large surge margin. As the SOFC is responsible for the main electrical power output, the efficiency of the MGT power module is of lower interest compared to the surge margin.

The project showed that the improved power module has to be further improved in terms of robustness for the integration into a hybrid power plant.

4.3.2 Combustor

The combustor of the MGT is also one core component for a hybrid power plant. It has to start-up the system, heat up the SOFC and has to deal with the low calorific anode exhaust gas and the depleted air of the cathode side of the SOFC during operation. In addition, the pressure difference between air (cathode exhaust) and fuel (anode exhaust) is limited. Therefore, a special combustion chamber has been designed based on the FLOX® principle [8] with a new liner concept [9],[10],[11],[12],[13],[14] shown in Figure 9.

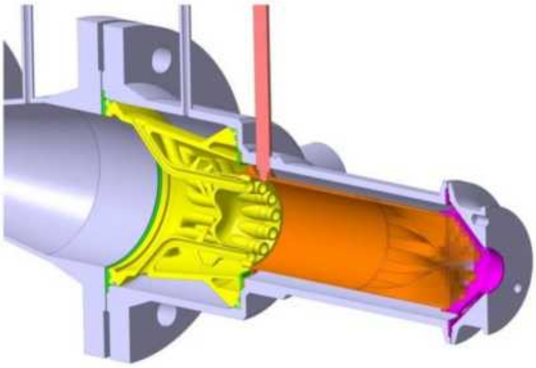

Figure 9: Combined MGT/SOFC-Offgas combustion system including pressure casing [14]

This combustor already showed a wide operation range, but it was found that there are some limitations where additional fuel would be needed for a stable combustion. The combustor concept can be used for the hybrid power plant but a possibility to inject additional fuel is needed. Maybe adding a second stage – a pilot burner to the combustor head is a suitable solution.

4.3.3 Recuperator

The recuperator is an air/air heat exchanger. It is used to exploit the hot exhaust gases for preheating the pressurized air after the compressor.

Figure 10: Optimized Recuperator from Hiflux integrated into MGT test rig: on the left without heat insulation on the right with heat insulation [15]

In the chosen hybrid power plant configuration the recuperator is implemented in between the vessel purge and the entrance to the SOFC cathode side. Therefore the pressure loss of the recuperator affects the pressure difference between the SOFC inside the cathode and the surroundings of the SOFC. Here, only a minimum pressure loss of 50 mbar is allowed. In the scope of the project the recuperator was optimized with regard to minimized pressure loss on the high pressure side. The improved recuperator is shown in Figure 10 implemented in the test rig (on the left) and equipped with heat insulation (on the right).

It has been shown that the optimized recuperator shows a pressure loss below the allowed value in all load points. Therefore, the component recuperator could be integrated into the hybrid power plant without additional adaptions pressure-loss wise. Yet, the connection from recuperator to SOFC needs to be optimized to reduce heat losses in this area.

4.3.4 SOFC

The chosen fuel cell for the hybrid power plant was a planar, electrolyte supported SOFC. This type of fuel cell does not show that high effect of the pressurization on the achieved electrical power output as an anode-supported cell, but has other advantages for pressurization like the increased thermo-mechanical stability. During the experiments it has been proven that this type of fuel cell can be used for a hybrid power plant. But for a commercial product the SOFC has to be re-designed to minimize the size of the pressure vessel. Hereby, the heat losses should also be minimized (see chapter4.3.4.2). Also, the fuel cell casing needs additional changes, as described in chapter 4.3.4.1.

4.3.4.1 Fuel cell casing

For the integration of an SOFC into a pressure vessel, the casing has to fulfil additional requirements. As the pressure surrounding the casing and therefore also the SOFC is slightly higher than the pressure inside the stack, the casing has to withstand this pressure difference even at operation temperatures of several hundred degrees centigrade. With respect to this, the casing needs to be optimized for future applications.

4.3.4.2 Heat insulation and piping system

The experiments showed a major influence of the heat losses to system performance and also to operation limits. Previous simulations did already show that heat losses will play a major role [18]. However, in addition to the considered losses, an increase of the heat losses with pressure was found. The two separated test rigs showed limited operation ranges due to these heat losses. For a real coupled hybrid power plant it is essential to minimize them. This could be done by using insulation materials with a lower pressure dependency of its insulation property, and by optimizing the assembly of the system components. The length of the tubing system has to be minimized. During the project a first attempt, which is shown in Figure 11, was done to investigate the smallest assembly possibility.

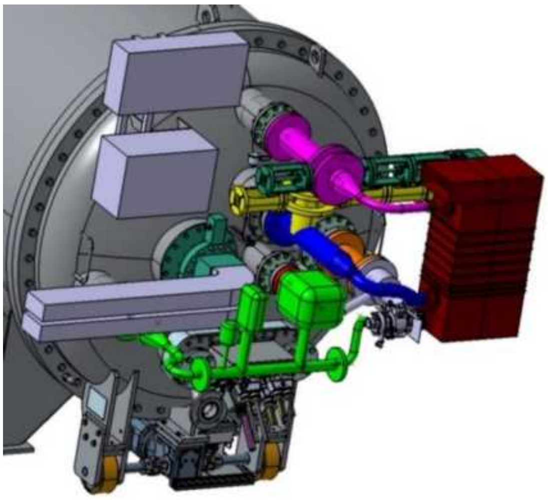

Figure 11: First draft of an optimized packaging of the components in a hybrid power plant

4.3.5 Recirculation blower

The recirculation blower is a major component in the SOFC system as it recirculates part of the anode gas to provide the water content and heat needed for the reforming reaction in the reformer and preheats the fresh fuel. Studies have shown that ejectors do not show a sufficient operation range and flexibility for a demonstrator. The chosen blower works, but as it is a prototype in size, improvements in its robustness are essential. In cooperation with the manufacturer the durability for this kind of application has to be improved.

4.3.6 Desulphurization and reformer

The device for the removal of sulphur in the natural gas works properly and is suitable for a hybrid power plant. The chosen reformer itself shows good results.

One major problem for the use of natural gas or biogas as a fuel is the insufficient heat supplied by the recirculation of the anode off-gas. The reformer outlet temperature drops by the endothermic reforming reaction of hydrocarbons. Thus, the maximum amount of natural gas reformed is limited by the minimum allowed temperature at the reformer outlet or anode inlet. Due to heat losses it was not possible to use 100 % natural gas or biogas. It is necessary to optimize the heat integration and minimize heat losses by better insulation and shorter tubes to overcome this problem. It may be useful to develop an additional heat exchanger to further preheat the incoming fuel, possibly using the hot exhaust gases at the anode or cathode outlet. Furthermore, a higher recirculation ratio by using a larger blower could be used. However, that would lead to higher pressure drops on the anode side of the SOFC and thus higher pressure differences at its inlet which may cause mechanical problems.

4.3.7 Grid connection

For the connection of the system to the grid a special design was used to prevent for damages when the grid is not healthy. Normally a power plant has to shut down when grid problems occur. In a hybrid power plant it may be of interest to bridge a certain time a grid failure and to have the possibility of a safe shutdown. The special design system for the facility is composed of a normal grid connection and a thermal resistor. In case of grid failure the system changes from the grid connection to the resistor.

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5 Conclusion

For the development of a hybrid power plant demonstrator a concept was developed. Therefrom, two separated test rigs were derived where one component each was replaced by emulation devices. Hereby, the characteristics and the behaviour of the subsystems MGT and SOFC could be investigated without harming the other system. The experiments were used to validate the chosen concept and define necessary adaptions.

It was found that in principle the layout can be used in a hybrid power plant. The chosen main systems MTT EnerTwin and Sunfire SOFC are suitable. For the real coupling some modifications and optimizations are still necessary. Especially the control system has to be revised. Here, in minimum feed forward controls have to be implemented. It has to be considered to change the concept from PID to other types of controllers. With the concept of only PID control the demonstrator cannot reach the requirements for a highly flexible system to react on changing power demands.

The focus for future investigations has to be set on the assembly of the parts and therefore on the minimization of heat losses. Heat losses are in this configuration a major issue leading to a limited operation range.

The components have to be optimized further according to the given open issues:

- Air bearings are mandatory for the system. Otherwise lubricants would be needed without sulphur or other harmful substances for the SOFC.
- The combustion system already achieved an extremely wide operational range. But especially with changed boundary conditions due to different heat losses, the operation limits were reached. The investigation of an additional stage (a pilot stage) could increase the operation range.
- With the optimization of the recuperator the minimized pressure drop was achieved. The focus is now on the connection from the recuperator to the SOFC to prevent heat losses.
- The recirculation blower has a lot of advantages compared to an ejector. The main focus is on the improvement of the reliability and the adaption to higher temperatures.
- The SOFC casing has to be adapted.

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