Grant No.: 641073

Bio-HyPP

Deliverable No	Title	Submission Date	Due	WP/Lead
D2.5	SOFC Auxiliary component characterization	14.06.2017		WP 2 / MTT

Short Summary

Auxiliary components of the SOFC system (reformer, anode gas recirculation device) were investigated. In the hybrid system all devices will be operated with different biogases. The influence of biogas on the devices was investigated theoretically and experimentally.

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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)	

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Table of Contents

Table of Figures

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1 Description of Deliverable and Motivation

Besides the fuel cell itself, an SOFC system usually consists of different auxiliary components such as reformer, gas recirculation, piping and off gas burner. The anode gas loop with reformer and gas recirculation device is very important for the operation of an SOFC system. It strongly influences the operating conditions and gas recirculation can help to increase the fuel utilisation of the system. This is important as fuel utilisation is a key parameter to achieve high electrical efficiency.

Figure 1 shows the general setup of the anode recirculation loop. Fuel is supplied to the system and prereformed inside the reformer. The steam and heat that is needed for the reforming is provided by recirculation of anode exhaust gas.

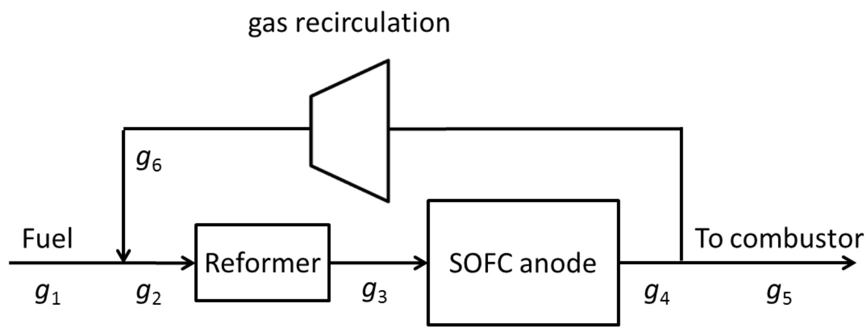

Figure 1: Schematic of the anode gas path of the hybrid power plant.

In this report it is summarised which reformer and recirculation device were chosen for the SOFC system. For gas recirculation two ejectors and a high temperature blower were tested. Furthermore, thermodynamic calculations were analysed with the focus on system operation with biogas.

2 Thermodynamic evaluation of anode gas recirculation and reforming

Recirculation of anode exhaust gases can provide heat and steam for fuel reforming and increase the fuel utilisation of a SOFC system. Thermodynamic calculations were carried out in order to predict gas composition and fuel mass flows for experimental investigations of SOFC stacks (see D2.2). Similar calculations were also used to predict operating conditions and specifications for reformer and gas recirculation device.

The aim of this analysis is to determine which recirculation rates are necessary for operation of the hybrid power plant. Furthermore, thermodynamic calculations are carried out to describe interdependency of the single pass fuel utilization (FU_{cell}), the system fuel utilization (FU_{sys}) and recirculation rate (R). The tendency towards carbon deposits is investigated. The fuel utilisation at the cell FU_{cell} is defined as the share of fuel that is being electrochemically converted while the gas passes once through the SOFC (g_3 vs. g_4). The system fuel utilisation FU_{sys} is defined as the share of fuel that is being electrochemically converted while the gas passes through the entire SOFC system (g_1 vs. g_5). Recirculation rate R is defined as

$$R = \frac{g_6}{g_4}$$

For evaluation of the tendency towards carbon deposits, thermodynamic equilibrium calculations were performed with the software package Cantera [1]. Calculations are carried out regarding 34 C–H–O gas phase species including up to C3 hydrocarbons and solid graphite. Equilibrium is calculated at the reformer outlet where the likelihood for carbon deposits is highest due to the low oxygen content and low temperature. Calculations were carried out in a range of temperatures (550–850 °C) and pressures (0.1–0.5 MPa) that are relevant for the hybrid power plant operation. Three different fuel compositions (g_1) were regarded:

Natural gas: 100 % CH_4

Biogas 75/25: 75 % CH_4 + 25 % CO_2

Biogas 50/50: 50 % CH_4 + 50 % CO_2

The results of the calculations are illustrated in Figure 2 for four different system fuel utilizations ranging from 24 to 90 % (solid lines). High system fuel utilization can either be achieved with high FU_{cell} or large recirculation rates. For a realistic FU_{cell} of 70 %, a recirculation rate of 74 % is needed to achieve a desired system fuel utilization of 90 %. These results are independent of temperature, pressure and fuel composition.

The dashed lines indicate the carbon formation boundary. Carbon is likely to form below the dashed lines. Carbon deposits are less likely with increasing FU_{cell} and increasing recirculation rate. With natural gas as fuel at a pressure of 0.1 MPa (top left diagram of Figure 2) carbon forms between 78 % (at FU_{cell} = 30 %) and 55 % (at FU_{cell} = 90 %) recirculation rate. Carbon formation becomes less likely with increasing temperature with smaller temperature effects at higher temperatures. Pressure dependency is small. An increase in pressure mainly results in a more even temperature dependency.

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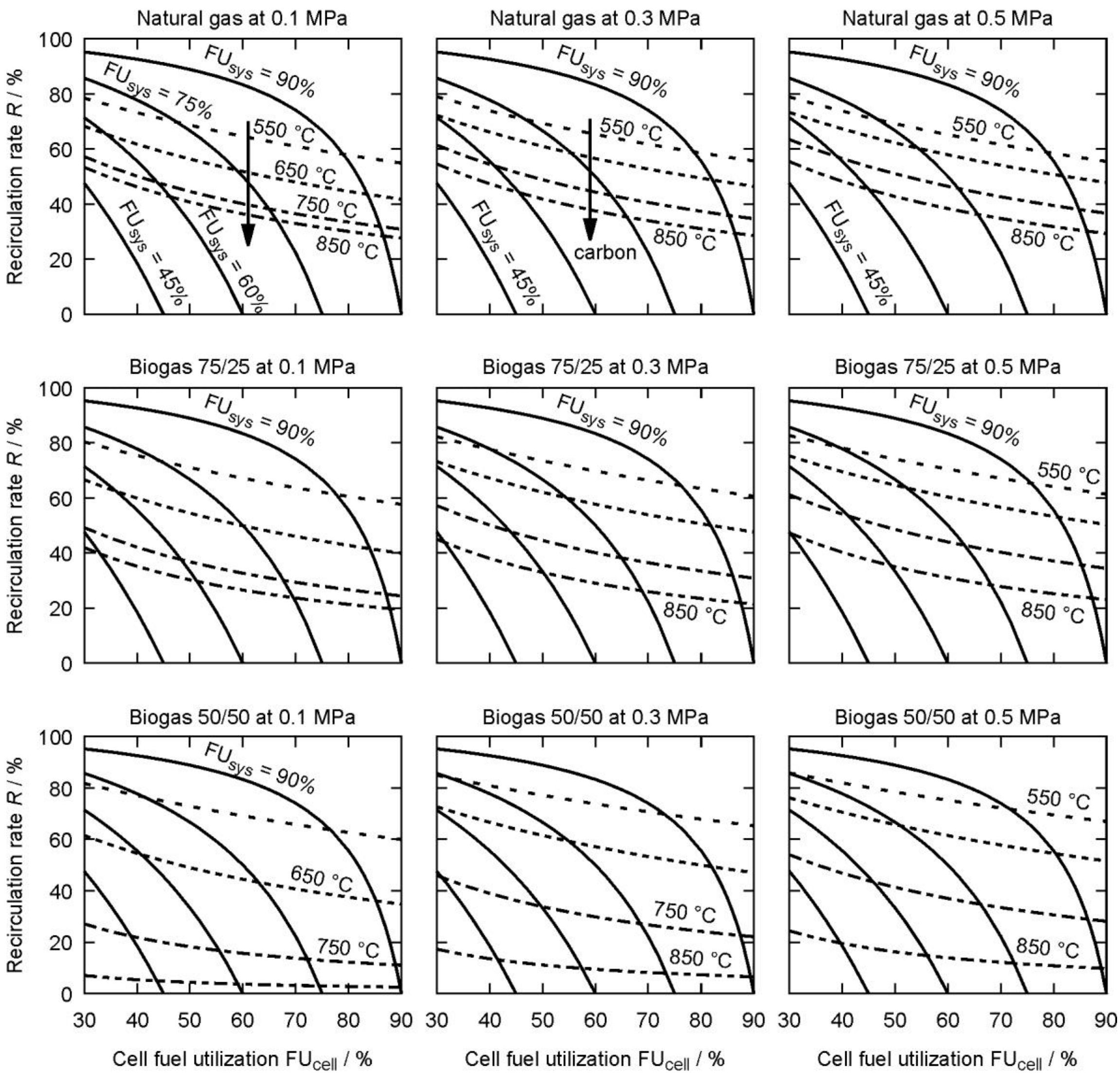

Figure 2: The diagrams show the dependency of FU_{sys} on FU_{cell} and recirculation rate *R* (results are independent of operating conditions). Carbon deposits are likely below the dashed lines for different temperatures, pressures and gas compositions.

Operation with biogas 75/25 yields a stronger temperature dependency at all pressures. At lower temperatures, carbon deposits are more likely thus higher recirculation rates are necessary. At high temperatures an increase in CO_2 content reduces the likelihood of carbon deposits. This effect becomes stronger with biogas 50/50 where hardly any recirculation is needed at 850 °C. For both biogases the tendency towards carbon deposits increases with increasing pressure.

Overall, the results show that operation is generally feasible with recirculation rates above 75 % at an estimated reformer outlet temperature of 600 °C. With increasing pressure and increasing CO2 content of the biogas, the likelihood for carbon deposits increases. At these conditions even higher recirculation rates should be considered.

3 Evaluation of reformer

The tubular reformer is located in the pressure vessel. It is integrated into the piping between the vessel wall and the anode inlet of the fuel cell. The recircled anode off gas is mixed to the fuel prior to the reformer to provide the necessary steam and heat for the steam reforming reaction.

The honeycomb-shaped substrate is a ceramic monolith based on aluminium oxide and calcium aluminates. The cell density is 600 cpsi. The catalyst itself is based on noble metals and manufactured by Johnson Matthey plc. Six thermocouples are implemented to investigate the radial temperature distribution at inlet and outlet of the catalyst.

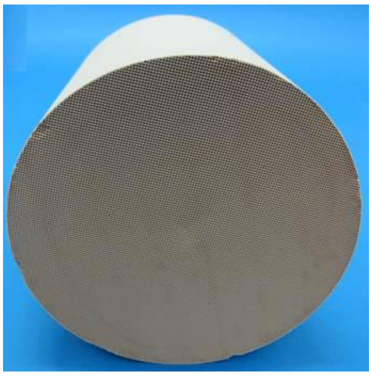

Figure 3: Catalyst

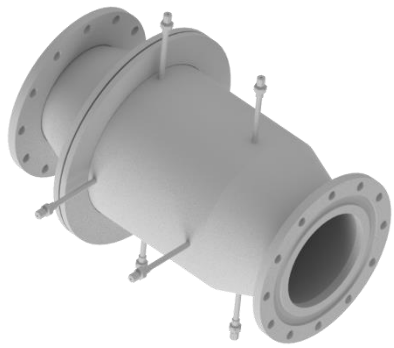

Figure 4: CAD sketch of the reformer

Due to the recirculation of the anode off-gas the mass flow through the reformer is higher than in a conventional SOFC system. Furthermore, biogas has a lower heating value what further increases the mass flow. In the hybrid power plant the differential pressure between anode and cathode is a critical parameter due to the mechanical stability of the electrolyte. Therefore the pressure loss of the reformer has to be investigated.
A test rig was set up to measure the pressure loss of air under atmospheric conditions. The results (see column 'Experiment' in Table 1) were used to calculate the discharge coefficient $\zeta_{\mathrm{reformer}}$ and to extrapolate the results to operating conditions by adapting Bernoulli's principle:

$$\Delta p_{loss} = \frac{\rho\, u^2}{2} \zeta_{\mathrm{reformer}}$$

Afterwards a system simulation is used to estimate the pressure loss in the running system. For the simulation a recirculation ratio of *RR* = 80 % and a SOFC temperature of T_{SOFC} = 1125 K were defined. The boundary conditions for these simulations are listed in Table 1.

Table 1: Boundary conditions for the pressure loss estimation

		Experiment	Simulation							
			Methane				Biogas			
SOFC Power	kW		21.0	25.0	30.0	35.0	21.0	25.0	30.0	35.0
Mass flow	g/s	38.0	13.3	15.9	19.3	23.0	23.4	28.0	34.4	41.4
Inlet pressure	bar	1.01	1.86	2.12	2.51	3.03	1.87	2.13	2.53	3.03
Inlet temperature	°C	15.0	738	741	742	743	750	754	757	759
Inlet molar mass	g/mol	28.8	30.3	30.0	29.6	29.2	24.9	24.4	23.9	23.3

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Combining the experimental data and the simulation results results in an expected pressure loss that is lower than 10 mbar even for biogas operation (see Figure 5). This pressure loss is in a tolerable range. However, the pressure loss is only extrapolated. Therefore a validation has to take place after the commissioning of the SOFC test rig.

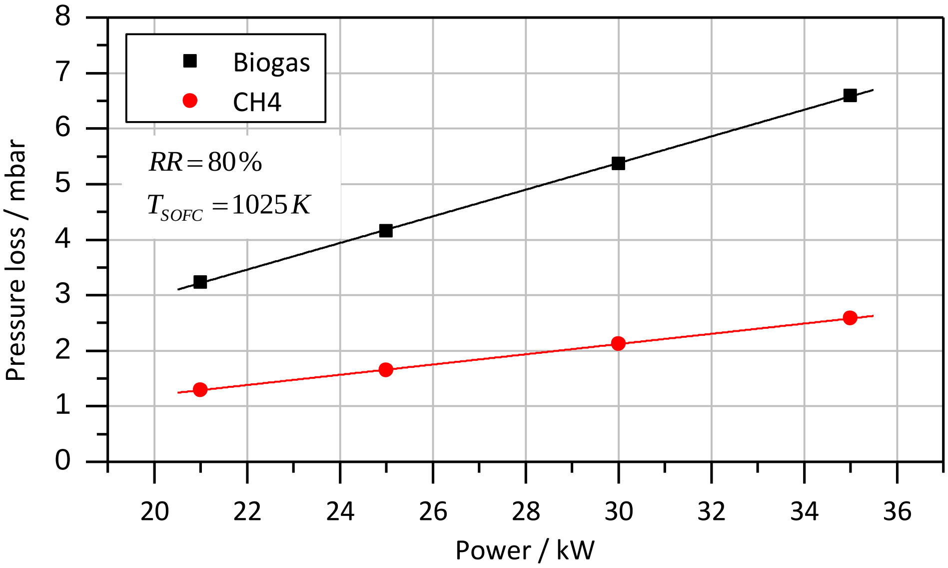

Figure 5: Expected pressure loss in the reformer

Aside from the assumptions made in the calculation, the experiment and the simulation can be inaccurate. Therefore the impact of such inaccuracies was investigated.
Values with the index 'sys' represent the actual values in the real system, values with the index 'exp' represent the values in the test rig. The index 'meas' describes values that were measured in the test rig and the index 'sim' values that were generated by system simulations.
The following points describe the uncertainties and their behaviour:

1. The pressure loss during the experiment could have been higher than measured:
$$\frac{\Delta p_{\mathrm{sys}}}{\Delta p_{\mathrm{sim}}} = \frac{\Delta p_{\mathrm{exp}}}{\Delta p_{\mathrm{meas}}}$$
2. The mass flow during the experiment could have been lower than measured:
$$\frac{\Delta p_{\mathrm{sys}}}{\Delta p_{\mathrm{sim}}} = \left(\frac{\dot{m}_{\mathrm{exp}}}{\dot{m}_{\mathrm{meas}}}\right)^{-2}$$
3. The mass flow that was simulated could be too low compared to the real system:
$$\frac{\Delta p_{\mathrm{sys}}}{\Delta p_{\mathrm{sim}}} = \left(\frac{\dot{m}_{\mathrm{sys}}}{\dot{m}_{\mathrm{sim}}}\right)^{2}$$
4. The gas density (representing the gas composition) that was simulated could be too high compared to the real system:
$$\frac{\Delta p_{\mathrm{sys}}}{\Delta p_{\mathrm{sim}}} = \left(\frac{\rho_{\mathrm{sys}}}{\rho_{\mathrm{sim}}}\right)^{-1}$$

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4 Evaluation of anode gas recirculation

Two different technical options are considered for anode gas recirculation in the SOFC systems. The first option is an ejector. It strongly reduces the fuel pressure by accelerating the fuel in a nozzle to very high speeds. The low pressure is then used to suck anode off gas into the fuel. Afterwards it is slowed down and pressure is increased again. Ejectors are comparatively cheap and can withstand high temperatures but lack the possibility to control the amount of recirculated gas. The second option that is considered is a blower. Gas flow can be controlled by changing the blower speed. However, these devices are technically ambitious if operating temperature is high and thus expensive. Both options were analysed experimentally. Eventually, the blower was chosen for the hybrid power plant as desired recirculation rates cannot be achieved with the tested ejectors.

4.1 Ejector

Two different ejectors were evaluated for use in the hybrid power plant. Ejector 1 was designed according to DLR-specifications for the desired gas compositions, gas flows, temperatures and recirculation rates. However, the supplier already stated prior to delivery that the desired recirculation will be difficult to achieve. Ejector 2 is an off-the-shelf device with the option to modify some of its geometric parameters.

A test rig was designed for evaluation of both ejectors and is shown in Figure 6. Gas mixtures of argon and helium were used to simulate the molar masses of the gases at the different locations of the system. At the fuel inlet, both gases were mixed to achieve the molar mass of methane. At the ejector outlet where the SOFC will be placed, additional argon is added to simulate the oxygen flow from cathode to anode. Real gases were not used to keep a simpler test rig layout and for safety reasons. The pressure drop along the SOFC was simulated using a manual valve. The recirculated gas flow was measured using a flow meter. Gas temperatures were adjusted between room temperature and 200 °C (maximum temperature of flow meter). Pressure was adjusted using another manual valve at the test rig outlet.

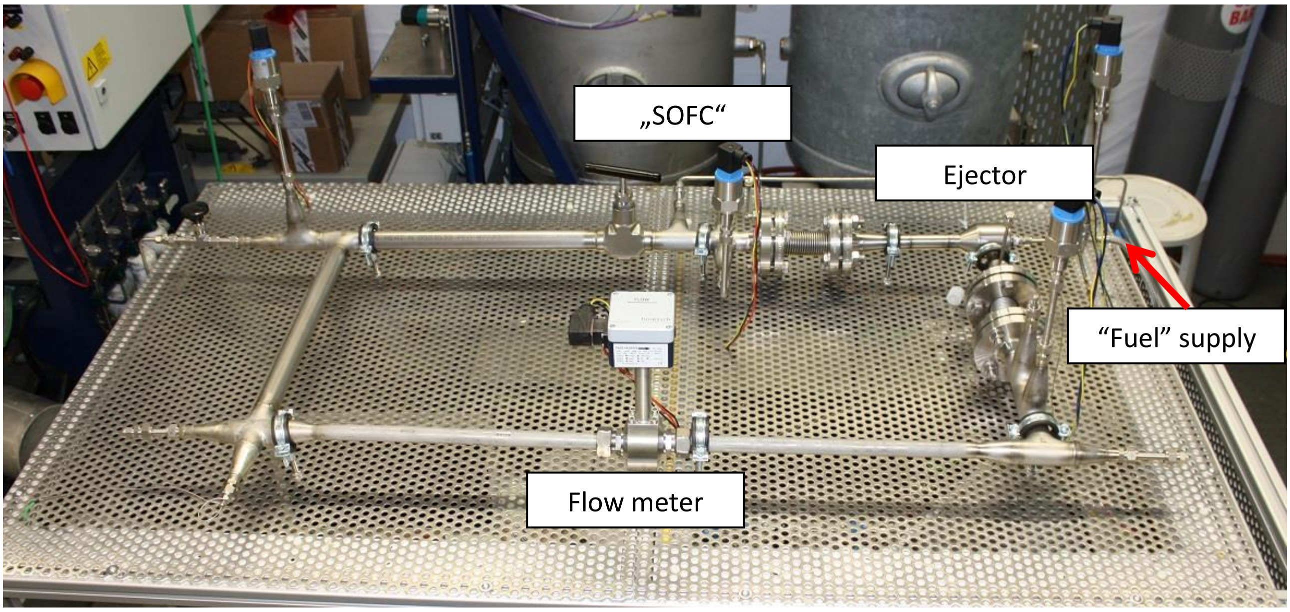

Figure 6: Ejector test rig (shown without electrical heating and thermal insulation)

Test results with both ejectors are shown in Figure 7 for two different electrical power outputs of the hybrid system. Operating conditions of the ejector were previously calculated using system models. The manual valve was set to a pressure drop of 30 mbar along the SOFC at P_{max}, $R = 0.75$ and 800 °C SOFC temperature. The valve position was not changed during these measurements.

Results show that ejector performance only slightly changes with the power output of the system. Similar recirculation rates can be achieved for both powers. Ejector 1 achieves recirculation rates around 0.8 at room temperature whereas ejector 2 only reaches about 0.65 at equal conditions. Recirculation rate is reduced with increasing temperature.

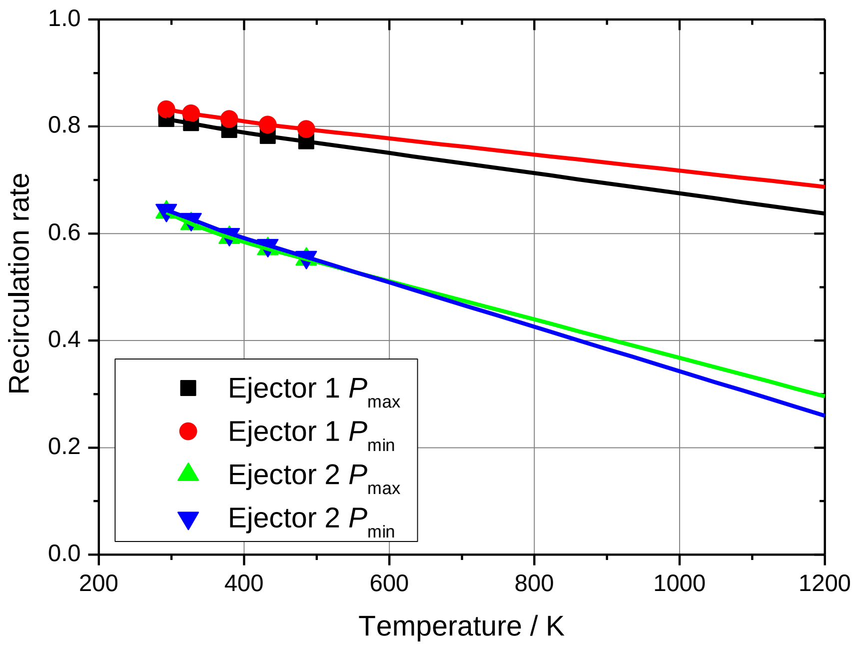

Figure 7: Achievable recirculation rate using ejectors

The results were extrapolated to SOFC operating temperatures. At relevant temperatures (950–1150 K) the recirculation rates with ejector 2 are below 40 % and therefore by far too small for the hybrid power plant. Much higher recirculation rates are achievable with ejector 1. However, the desired recirculation rate of 75 % (see chapter 2) cannot be reached, especially at high electrical power of the hybrid plant. Therefore, both ejectors are not further considered for use in the hybrid power plant.

4.2 Blower

As the tested ejectors were not suitable for the hybrid power plant, blowers that can meet the requirements were checked. For the hybrid power plant the blower SSR70-Ns300 of the Japanese company CAP Co., Ltd was tested. The specifications in the design points are listed in Table 2. Unlike most other recirculation blowers used in SOFC systems the CAP blower can operate at SOFC outlet conditions; especially at SOFC outlet temperature. Therefore the off gas can be directly recirculated without cooling, resulting in a high system efficiency.

Table 2: Design parameters of the Blower

Parameter	Value	Unit
Volume flow	0.05	m^3/s
Speed	43500	min^{-1}
Inlet temperature	1133	K
Pressure difference	50	mbar
Gas density	0.52	kg/m^3

Prior to the implantation into the hybrid power plant it is necessary to characterize the blower with respect to two major points. Firstly, it has to be shown that the blower can provide the mass flow that is necessary. Secondly, a qualitative relation between mass flow and blower speed has to be established to define the transfer function of the control system.

Figure 8: CAP blower

Figure 9: Blower in the test rig

4.2.1 Blower test rig

A test rig was developed and built to characterize the blower (see Figure 9 and Figure 10). It consists of a gas supply system where H2, CO2, and N2 can be supplied. Due to safety reasons no CO is used but instead it is replaced by N2 as the differences in the molar masses, respective the densities are negligible. In addition, hot steam is supplied via an evaporator. The blower is integrated into a furnace together with a flow meter. The furnace can be heated up to operating temperature of the SOFC system. An orifice is used to simulate the pressure drop of the SOFC, reformer and piping. Pressure sensors at inlet and outlet of the furnace are used to measure the pressure drop. Additional N2 is supplied to the blower as purge gas.

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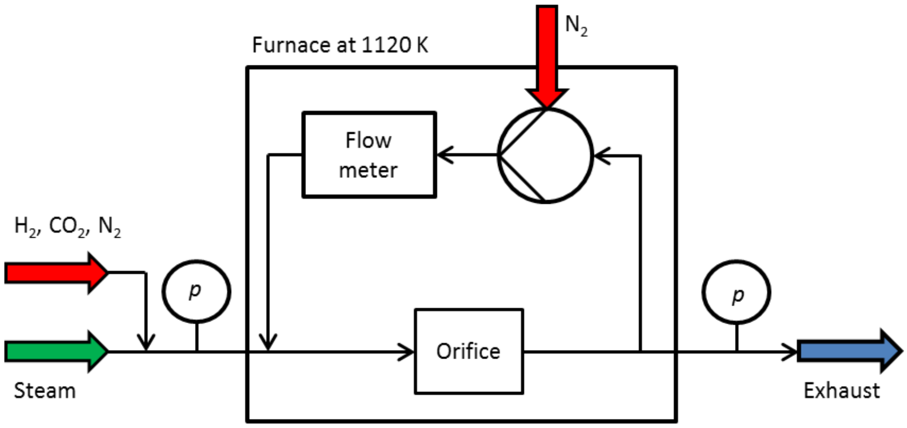

Figure 10: Schematic of the blower test rig

4.2.2 Experimental Results

The blower was operated using a variety of gas mixtures (see Table 3, hereafter called C1–C5) to investigate the behaviour of the blower in the different operation points of the hybrid power plant. The compositions C6 and C7 result from thermodynamic simulations of the hybrid power plant (WP1) representing a 20 and a 30 kW operating point. For these the recirculation ratio is varied. The composition varies only slightly with the recirculation ratio and is adapted accordingly in the test rig. The composition C6 and C7 in Table 3 are represent a 20 and a 30 kW operating point with 80 % recirculation.

Table 3: List of gas compositions used in the experiments

Composition	Molar fractions				Comment
	X_{CO2}	X_{N2}	X_{H2O}	X_{H2}	
C1	0.278	0.079	0.562	0.081	Assumed full load
C2		0.960		0.040	Assumed start up
C3		0.635	0.255	0.109	Assumed transition
C4	0.289	0.074	0.540	0.096	Assumed minimum load
C5	0.180	0.184	0.380	0.256	Assumed load shedding
C6_80	0.286	0.048	0.579	0.088	Simulation of 30 kW with RR of 80 %
C7_80	0.312	0.021	0.628	0.039	Simulation of 20 kW with RR of 80 %

The pressure in the test rig cannot be controlled. It results from the pressure drop in the exhaust pipe that depends on the mass flows out of the test rig. Due to the equipment of the test rig (e. g. mass flow controllers, purge flows) a minimum mass flow has to be dosed, resulting in a minimum test rig pressure.

4.2.2.1 Evaluation

A linear behaviour between the mass flow and the blower speed can be observed for all gas mixtures (see Figure 11). However, the slope of the curves varies depending on the pressure in the test rig and the composition of the gas.

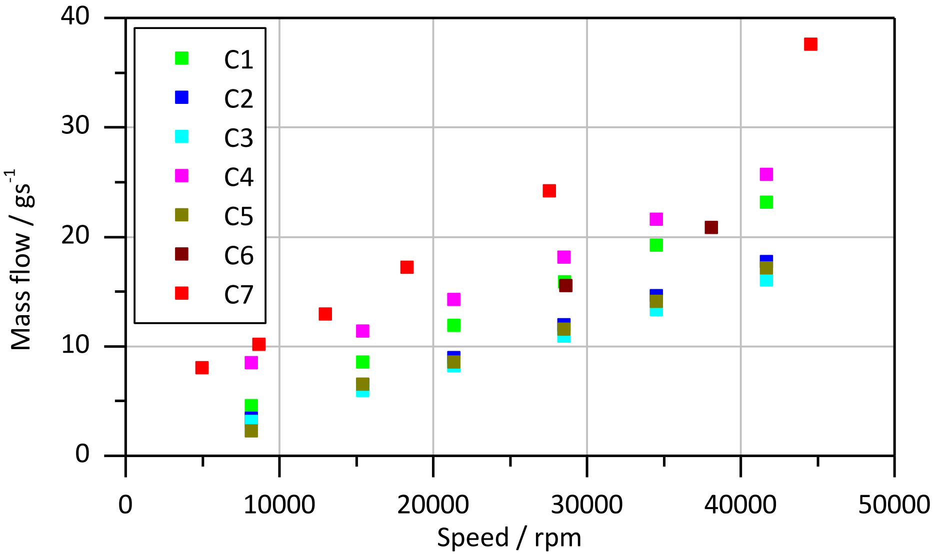

Figure 11: Results of the blower characterization experiments

To make up for that, referred parameters are introduced which are derived from the known gas turbine theory. The axial and radial Mach numbers are equated for a reference point and the actual operating point. In contrast to conventional gas turbines the composition at the blower inlet changes significantly with the hybrid power plant operation point. Therefore the isentropic coefficient and the molar mass of the fluid cannot be neglected. The referred mass flow and the referred speed are defined as below:

$$\text{Referred mass flow:} \quad \dot{m}_{\text{ref}} = \dot{m}\frac{p_0}{p}\sqrt{\frac{T}{T_0}\frac{\kappa_0}{\kappa}\frac{M_0}{M}}$$

$$\text{Referred speed:} \quad n_{\text{ref}} = n\sqrt{\frac{T_0}{T}\frac{\kappa_0}{\kappa}\frac{M}{M_0}}$$

The reference point is a 30 kW operating point that uses pure methane as fuel. The resulting parameters of the reference point are listed in Table 4.

Table 4: Parameters of the reference point

Parameter	Pressure p_0	Temperature T_0	Isentropic coefficient κ_0	Molar Mass M_0
Value	3 bar	1023 K	1.122	24.50 g/mol

Applying the referred parameters to the experimental results leads to Figure 12. The slopes coincide for the different compositions.

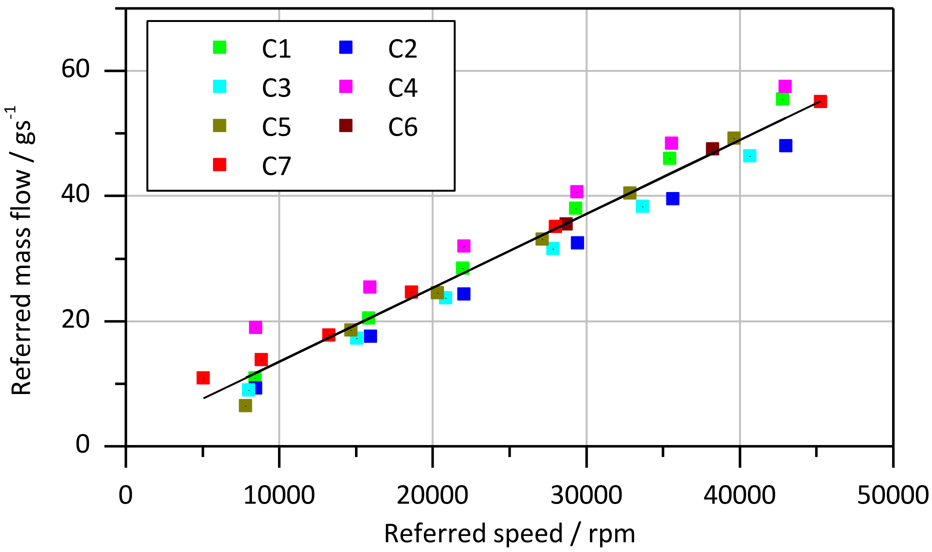

Figure 12: Correlation between referred mass flow and referred speed

Unfortunately the pressure loss of the piping of the test rig is not known and due to the damage of the test rig the orifice was not used to simulate pressure drops of reformer and SOFC. Therefore, it is not possible to create a compressor map from the experimental results. By using experimental data of CAP Ltd. the pressure loss of the test rig can be estimated. The data from CAP Ltd. contains a blower curve (see Figure 14) that was measured by increasing the back pressure of the blower at constant speed until the blower runs into surge.

From Bernoulli's principle it follows:

$$\Delta p_{loss} = \frac{\rho\, u^2}{2}\left(\lambda \frac{l}{d} + \Sigma\zeta_i\right) = \frac{\rho\, u^2}{2}\zeta_{\text{tot}}$$

The Darcy friction factor λ and the discharge coefficients ζ depend on the flow condition ($\lambda = f(Re)$, $\zeta_i = f(\rho, u)$). Furthermore it is challenging to find these parameters even for on operating point without a detailed investigation of the flow conditions in the components (e. g. SOFC). Therefore the lumped parameters $c_{\text{test rig}}$ and c_{system} are used in a modified Blasius correlation for the Darcy friction factor formulae:

$$\Delta p_{loss} = \frac{\rho\, u^2}{2}\lambda_i \frac{l}{d} = \frac{\rho\, u^2}{2}\frac{c_i}{\sqrt[4]{Re}}\frac{l}{d}$$

At a point with the same referred speed and the same referred mass flow also the pressure ratio has to be the same. With that information the lumped parameter $c_{\text{test rig}}$ can be calculated. The pressure drop in the hybrid power plant will be higher. The piping is going to be in the same size and length as in the test rig. However, SOFC and reformer result in an additional pressure loss. The pressure loss of the SOFC was designed to be under 10 mbar in all operating conditions. The pressure loss of the reformer was calculated in section 3. As a first approach an additional pressure loss of 20 mbar (E1) in the reference operating point is assumed. Furthermore, this is compared to a 20 % higher pressure loss (E2).

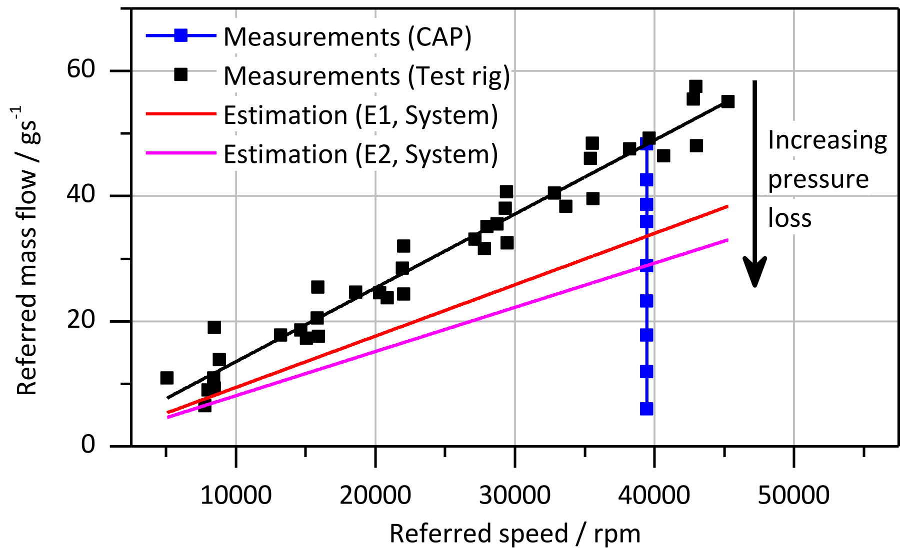

Figure 13: Mass flow reduction for higher pressure losses

A higher pressure loss leads to a lower referred mass flow if the referred speed kept constant. Therefore the estimated curves in Figure 13 move to lower flows. It was assumed that the quotient of the mass flow in the system and the mass flow in the test rig $\dot{m}_{\mathrm{system}}/\dot{m}_{\mathrm{test\ rig}}$ does not depend on the referred speed. With the calculated pressure losses the results can be shown in a blower map. (see Figure 14)

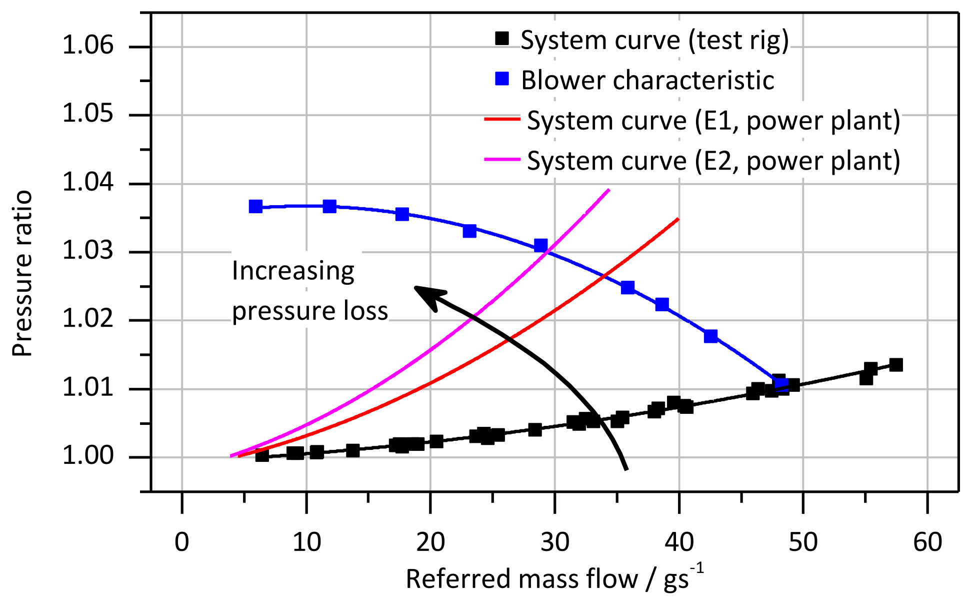

Figure 14: System curves for different pressure losses

The test rig system curves take the measurements and the calculated pressure drop inside the test rig into account. By increasing the pressure loss the characteristic system curve moves along the characteristic blower curve. This results in a new characteristic system curve.

By using a system model to simulate operating points for methane and biogas operation, it can be shown that the blower can handle the necessary mass flows. Table 1 shows the resulting blower speeds. The blower speeds for all operating points are lower than the design speed n_0 = 43.5 krpm.

Table 5: Resulting blower speed

System Power	SOFC Power	Recirculation ratio	Blower speed (E1)	Blower speed (E2)	Fuel
kW AC	kW DC		krpm	krpm	
21.5	21.0	0.80	32.7	38.0	50 % CH4, 50 % CO2
21.5	21.0	0.80	23.0	27.0	100 % CH4
26.0	25.0	0.80	34.8	40.6	50 % CH4, 50 % CO2
26.0	25.0	0.80	24.5	28.7	100 % CH4
31.8	30.0	0.80	36.3	42.4	50 % CH4, 50 % CO2
31.7	30.0	0.80	25.6	30.0	100 % CH4
37.7	35.0	0.80	36.7	42.8	50 % CH4, 50 % CO2
37.6	35.0	0.80	26.0	30.4	100 % CH4

For even higher pressure losses the blower could exceed its limits. Especially for biogas the desired recirculation rates could be unachievable.

Furthermore, the pressure loss is only calculated and contains various assumptions. The real pressure loss cannot be determined as no pressure cells are implemented in the hot parts of the SOFC system. Therefore calculations have to be performed to validate the characteristic curve. An energy balance around the reformer can be used to connect the recirculated mass flow and the temperature drop over the reformer (see section 4.2.2.3).

4.2.2.2 Implementation into the control system

The new curve can be implemented into the control system and can be used in the system simulations.

For the implementation into the control system the required accuracy is lower as the controller will adjust the speed continuously. In the referred parameters the composition dependent terms (M, κ) will be neglected. This has the advantage that compositions do not need to be calculated from the control system. The additional error will be around 2 %. The resulting error for the recirculation rate is even smaller.

During the evaluation of the experiments the calculation can be performed using the complete equations for the referred parameters.

4.2.2.3 Further evaluation and validation

Due to the high number of assumptions it is necessary to evaluate the calculations. Therefore a different approach to calculate the recirculation mass flow will be developed. Depending on the recirculated mass flow the temperature drop of the reformer will change. This temperature drop will be measured as well as the temperatures of the fuel and recirculation mass flow. By assuming equilibrium at the outlet of the reformer and at the outlet of the SOFC all relevant compositions can be calculated. Using an energy balance for the reformer will lead to the recirculated mass flow.

These calculations can be used to tune the pressure loss model and update the control system.

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4.2.3 Blower cooling failure

Impeller and piping of the blower are inside the pressure vessel while motor and bearings are outside. As heat is transferred from the impeller to the outer parts an active cooling is implemented by the supplier. A heat sink is attached to the blower and cooled with an air fan.

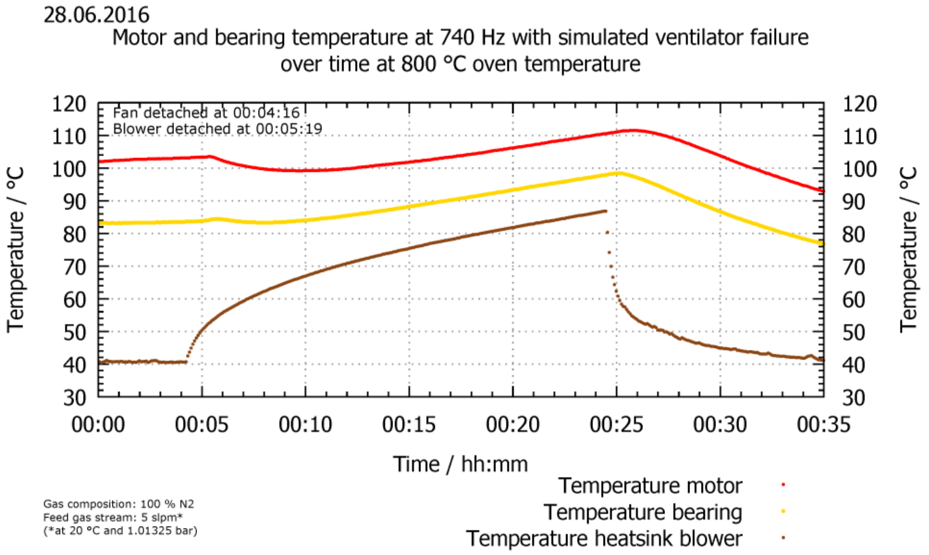

Figure 15: Temperature increase due to simulated cooling fan failure

The maximum temperature for motor and bearing is 120 °C A test is performed to simulate a fan failure. The results are shown in Figure 15. The fan was detached after 4.27 min and the blower was shut down at after 5.32 min.

Around 20 minutes after the failure of the cooling fan the motor and bearing temperatures reach a critical level and the fan was started again. As the blower is an important and expensive component of the hybrid power plant a mitigation strategy is implemented. The standard fan is replaced by two redundant fans with speed sensors. In case of a failure of one fan a safe shutdown procedure will be carried out.

In the reals system the temperature in the vessel will be under 400 °C. This is lower than the oven temperature in the experiment. Therefore the temperature will increase slower.

5 Conclusions

In this report the SOFC auxiliary components have been described and analysed. The focus was on recirculation devices as these are one of the biggest challenges for SOFC systems with anode off-gas recirculation. Section 4.1 described the tests of the different ejectors. These have shown that an ejector is not suitable for the hybrid power plant as the achievable recirculation ratio is too small and cannot be controlled. However, the examined recirculation blower can achieve the desired recirculation rates for methane and biogas operation. By varying the speed the recirculation ratio can be controlled.

During the experiments a test rig failure occurred and not all planned experiments were carried out. However, the data is enough for the operation of the hybrid power plant. Repairing the test rig would have been very time consuming and the recirculation device is needed for the commissioning of the SFOC test rig. Therefore calculations and simulations were performed instead. These calculations are using assumptions that have to be validated. During the operation of the hybrid power plant the assumptions will be checked and, if necessary, improved.

In conclusion, the SOFC auxiliary components, both reformer and recirculation blower, are suitable for the usage in a hybrid power plant.

Reference

[1] David G. Goodwin. An open source, extensible software suite for CVD process simulation. *Electrochemical Society Proceedings*, 8:155–162, 2003.