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

Grant No.: 641073

Bio-HyPP

Deliverable No	Title	Submission Date	Due	WP/Lead
D2.2	SOFC stack characterization and optimization	30.11.2016		WP 2 / MTT

Short Summary

Experiments with 10 cell SOFC stacks were carried out to determine the influence of CO_2 content (fuel) on SOFC performance. It was found that the influence is only marginal if all other operating conditions are kept constant.

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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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1 Description of Deliverable and Motivation

The increased CO_2 content of biogas compared to natural gas is expected to lead to lower SOFC stack voltage due to a decrease in Nernst potential caused by reactant dilution. This may result in the requirement of changing the process dimensioning. Therefore, the behaviour of a 10-cell SOFC stack is examined experimentally. Methane and biogas are used as fuel. The experimental data is used to serve as input for thermodynamic process analyses. Pressure is varied up to 8 bar to supply data also for other system configurations. This deliverable belongs to Task 2.3.1 of the project master plan.

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2 Experimental Set-up

Figure 1 shows the high pressure SOFC test rig that is used to carry out the experiments. The test rig is located at DLR premises in Stuttgart, Germany. It is capable of testing small planar SOFC stacks at pressures up to 8 bar. Different gas compositions (containing H_2, N_2, CH_4, CO, CO_2 and H_2O) can be applied at the anode via mass flow controllers or a water pump. This allows for testing of different biogas compositions which are relevant for this project.

The aim of these measurements is to predict the operation behavior of SOFC stacks of the hybrid power plant. Two different fuels were chosen to cover a range of biogases. A planar electrolyte supported 10 cell stack from sunfire is tested. The same cells will be used for the hybrid power plant, however in larger stack configurations of 120 cells.

All operating conditions were derived from thermodynamic system simulations (WP1). The chosen operating conditions are realistic for future power plant operation concerning pressure, temperatures, gas flows, gas conversion rates and recirculation ratios.

Figure 1: Test rig for characterisation of 10 cell stack at elevated pressure.

Figure 2 shows how the stack is integrated into the test rig. Anode and cathode gases are preheated to furnace temperature prior to entering the stack. The stack is located inside a welded box. It is equipped with 5 voltage measurements, each monitoring the voltage of a pair of adjacent cells. Furthermore, five thermocouples are integrated into the stack as illustrated in Figure 2. They are located inside the cathode gas channels towards the outlet at the hottest part of the cell. For the determination of the stack core temperature, the thermocouple T3 is used.

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Stack temperature control imposes the most relevant difference between these 10 cell stack tests and the real operation of stacks in the hybrid power plant. For these tests, the stack is heated externally by the furnace (here set to a temperature of 840 °C) and internally due to electrical resistances. Tests are carried out with fast current ramps of 0.117 A/cm^2/min (15 A/min) in order to keep the stack core temperature as constant as possible. In the hybrid power plant, the stacks are thermally insulated and heated mainly internally. Stack core temperature will be controlled by adjusting the air mass flow through the stack. Comparing these small scale tests and the operation inside the hybrid power plant, these differences will result in differences in temperature distributions inside the cells. Furthermore, stack insulation of small scale and system tests differs strongly. Furthermore, effects of internal methane reforming (endothermic reaction) are neglected. Nevertheless, stack core temperature is generally a good measure for an average temperature [1]with sufficient accuracy for system level predictions.

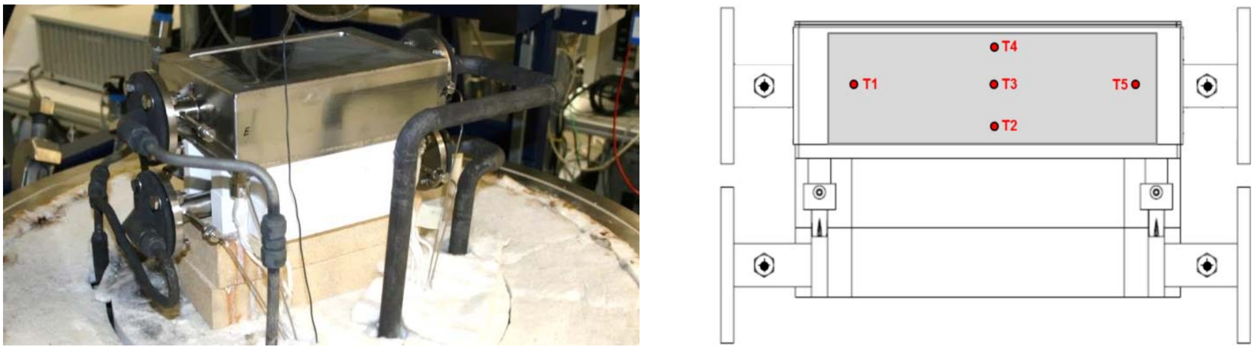

Figure 2: Left: Integration of 10 cell stack into test rig including gas supply and instrumentation. Right: Position of different thermocouples placed inside the cathode gas channels. Thermocouples are placed towards the gas outlet where the cells are expected to be hottest. T3 is defined to be the core temperature of the stack.

Pressure is set to three different values. Measurements at 3 bar are most relevant for the future operation of the hybrid power plant. Additionally, experiments are carried out at 1.4 and 8 bar in order to investigate how pressure effects the performance of the SOFC.

Experiments were carried out based on two different fuels: natural gas containing only CH_4 and biogas consisting of 50 % CH_4 and 50 % CO_2 (molar fractions). These gases were chosen as they cover a broad range of possible biogases. SOFC operation with biogases with lower CO_2 content can be derived from these results. In the hybrid power plant the gas composition at the anode inlet differs from the fuel composition due to the anode exhaust gas recirculation. Recirculation is necessary in order to preheat the fuel, to provide steam for the steam reforming, and to achieve high fuel conversion rates. A schematic of the anode recirculation loop is shown in Figure 3. Fuel is fed to the system and mixed with the recirculated exhaust gas. The fuel is pre-reformed and led through the SOFC anode where it is partly electrochemically converted. Parts of the exhaust is recirculated whereas the remaining part leaves towards the combustion chamber (not shown).

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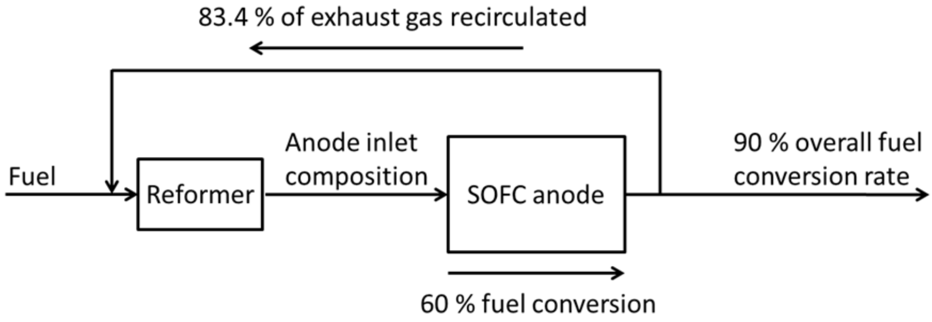

Figure 3: Schematic of the anode gas path of the hybrid power plant.

For the presented experiments it is assumed that 60 % of the usable gas (H_2, CO, CH_4) is converted into H_2O and CO_2 while passing through the SOFC once. The recirculation rate is assumed to be 83.4 % which results in an overall (system) fuel conversion rate of 90 %. Gas compositions are assumed to be in equilibrium at the reformer outlet / SOFC inlet and were calculated for 3 bar and 650 °C. Based on the above conditions, the methane content at the anode inlet is below 1 % for both fuels. This value is too low to be achieved with the available test rig infrastructure. Therefore, the methane and CO_2 content is reduced and additional H_2 and CO is added to keep the correct atomic composition of the gas. Eventually, the following anode inlet compositions (given in molar fractions) are used for the two different fuels:

Natural gas: 24.9 % H_2 + 41.8 % H_2O + 8.4 % CO + 24.9 % CO_2

Biogas: 15.7 % H_2 + 34.3 % H_2O + 9.3 % CO + 40.6 % CO_2

The gas mass flow is set to achieve the desired conversion rate of 60 % at a current density of 0.156 A/cm^2 (20 A). This reflects an intermediate power output of the hybrid power plant. Air was used as cathode gas. Air mass flow was adjusted to achieve an oxygen conversion rate of 35 % at the same current density.

3 Results and Discussion

Figure 4 and Figure 5 show the experimental results that were obtained with natural gas and biogas equivalent compositions for three different pressures. Results are qualitatively similar for both gases. The cell voltage shown here is the average of the two middle cells. Open circuit voltage increases with rising pressure due to an increase in Nernst potential. Further significant effects of pressure on cell voltage are not visible.

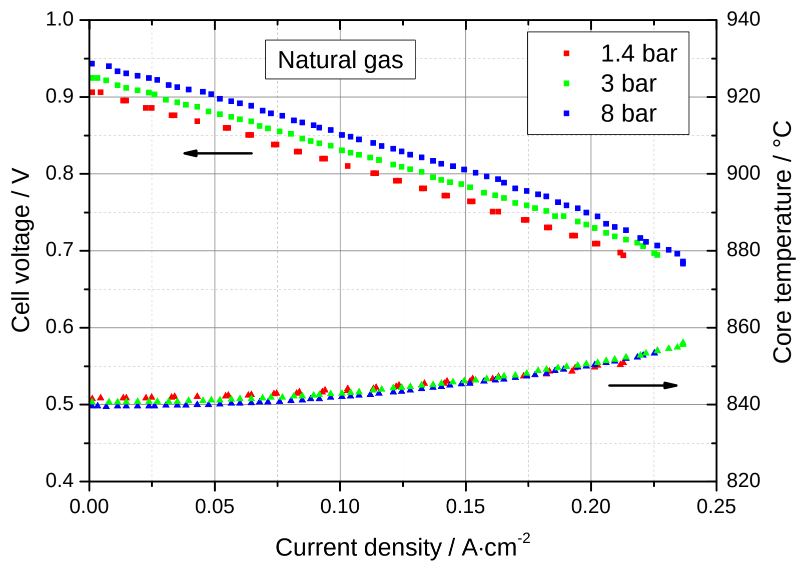

Figure 4: Experimental results for operation with natural gas equivalent.

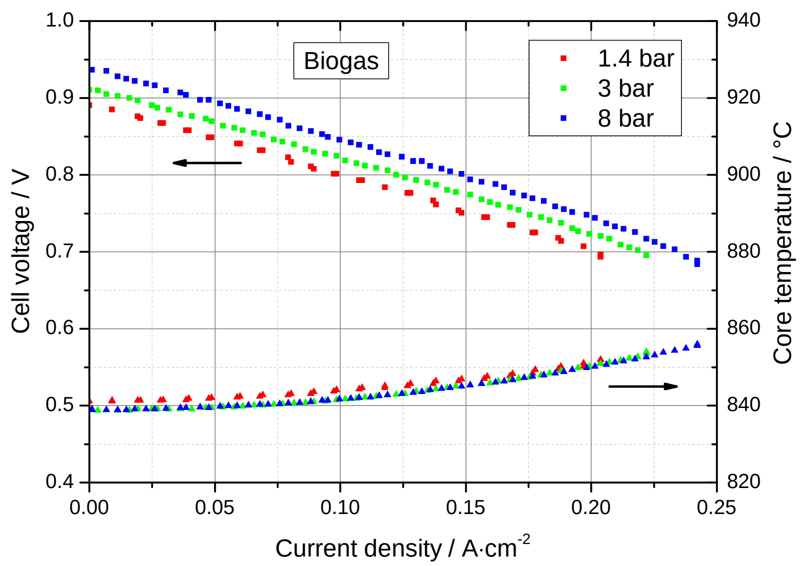

Figure 5: Experimental results for operation with biogas equivalent.

Figure 6 shows a comparison of operation with biogas and natural gas at a pressure of 3 bar. The difference in Nernst potential is clearly visible at open circuit voltage. With increasing current density this effect diminishes as fuel and product concentrations of both gases align. At the inspected operating point of 0.156 A/cm^2, the cell voltage is similar for both gases (0.77 V) and the power output of one cell is 15 W. Under these intermediate power conditions the electric power output of the SOFC module of the hybrid power plant would be 22 kW.

Stack core temperature (T3) increases with increasing current density despite the fast current ramps but stays below the stack temperature limit of 860 °C. Temperature is not influenced by fuel compositions thus the results are comparable. In the hybrid power plant, stack core temperature will be controlled via the air mass flow as described in Section 2.

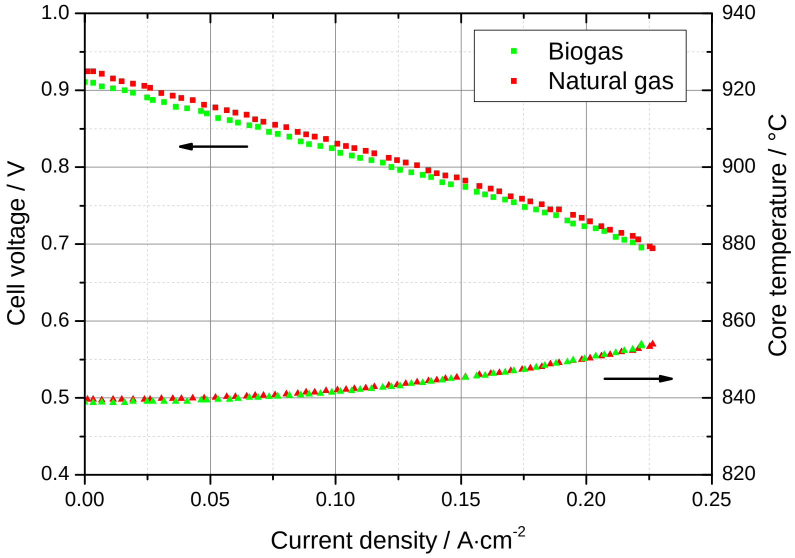

Figure 6: Comparison of operation with natural gas and biogas at a pressure of 3 bar.

4 Conclusions

The operation with natural gas (CH_4) and biogas (50 % CH_4 + 50 % CO_2) showed very similar results at otherwise equal operating conditions. It is concluded that the influence of fuel composition is negligible at cell level within the range of investigated fuels. Similar power output can be achieved with both fuels.

The experimental results on stack level can be widely applied to system level. For similar operating conditions of the SOFC module, similar power output can be achieved. However, the different fuel compositions also have an influence on the operating conditions. Especially the operating temperature has a strong effect on SOFC performance. Temperature of the anode gas is influenced by reforming and gas recirculation. Cathode gas temperature is affected by system components like the recuperator. The achievable gas recirculation ratio will also be affected by fuel composition. A final and overall evaluation of the influence of CO_2 content therefore needs to be carried out on system level.

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References

[1] C. Willich, A. Tomaszewski, M. Henke, K. A. Friedrich, and J. Kallo, "Temperature Effect due to Internal Reforming in Pressurized SOFC," *Journal of The Electrochemical Society*, vol. 161, pp. F674–F678, 2014.