



Development of a Solid Oxide Fuel Cell for the utilization of coal mine gas

B. Groß^{a,*}, L. Blum^b, L.G.J. de Haart^b, A. Dengel^c

^a IZES gGmbH, Altenkesseler Straße 17, D-66115 Saarbrücken, Germany¹

^b Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany

^c Evonik New Energies GmbH, St. Johanner Straße 4, D-66115 Saarbrücken, Germany

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ABSTRACT

Apart from natural gas there is another important natural source of methane. The so-called coal mine gas is a by-product of the geochemical process of the carbonization of sediments from marsh woods of the Earth's Carboniferous Period. Methane evaporates from the coal and has to be removed out of the active mines where it represents one of the main safety risks. Methane also evaporates in abandoned coal mines. In the federal state Saarland in Germany exists above ground a more than 110 km pipeline for the drained coal mine gas from 12 different sources. The content of methane varies between 25 and 90%, the oxygen content (from air) is in the range up to 10%. This wide range or variation, respectively, of fuel and oxygen content, causes a lot of problems for the use in conventional engines. Therefore the company Evonik New Energies GmbH is interested in using SOFC with coal mine gas as efficient as possible to produce electric power. For that purpose at Forschungszentrum Jülich the available SOFC technology was adapted to the use with coal mine gas and a test facility was designed to operate an SOFC stack (approximately 2 kW electrical power output) together with a pre-reformer.

This paper presents the results of the coal mine gas analysis and the effect on the pre-reformer and the fuel cell. The composition of the coal mine gas was determined by means of micro-gas chromatography. The results obtained from preliminary tests using synthetic and real coal mine gas on the pre-reformer and on the fuel cell are discussed.

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1. Introduction

In the year 2003 the project, funded by the German Federal Ministry of Economic Affairs and Technology, was started by the company Evonik New Energies GmbH, the former STEAG Saar Energie AG (Evonik) together with Forschungszentrum Jülich (JÜLICH) and the IZES gGmbH (IZES) [1]. The objective of this project was to demonstrate the feasibility of using coal mine gas efficiently in an SOFC. Because coal mine gas, as a by-product of the geochemical process of the carbonization of sediments from marsh woods, the methane content is variable between large concentration ranges. Coal mine gas contains also variable fractions of oxygen and nitrogen (both from air) as well as carbon dioxide and hydrocarbons. The possible variations are given in Table 1. For example the methane concentration in coal mine gas may vary between 30 and 90% [2]. Within the project the suitability of the existing SOFC technology developed by Jülich for that kind of gas had to be tested. Furthermore a special adapted pre-reformer technology and control unit had to be developed. The main tasks of Jülich were the

development, manufacture and test of the pre-reformer unit and the SOFC stack under laboratory conditions. Together with the partners Jülich developed a concept and control strategy for the test facility. Contemporary to the work of Jülich, Evonik and IZES constructed the test facility and process measuring as well as control technology for the pre-reformer and fuel cell tests with natural coal mine gas at the location in Luisenthal.

2. Properties of the coal mine gas in Luisenthal

The coal mine gas used within the framework of the project was taken from the coal mine gas network in the federal state of Saarland/Germany. This network is owned by the Evonik New Energies GmbH and has a total length of 110 km above ground. Using twelve drainage plants, partly connected to abandoned and partly to active coal mines, about 200 Mio m³ coal mine gas per anno, based on an average methane content of about 50%, is presently fed into the network using 42 gas extraction units with a capacity of about 90,000 m³ h⁻¹, by 29 gas compressors with a capacity of about 60,000 m³ h⁻¹ as well as 15 gas driers with a capacity of about 68,000 m³ h⁻¹. More than 90% of this amount is used for heat and power production. This corresponds to a yearly average power of approximately 126 MW. The network connects those twelve mine

* Corresponding author. Tel.: +49 681 9762 851; fax: +49 681 9762 175.

E-mail addresses: schlichter@izes.de, gross@izes.de (B. Groß).

¹ <http://www.izes.de>.

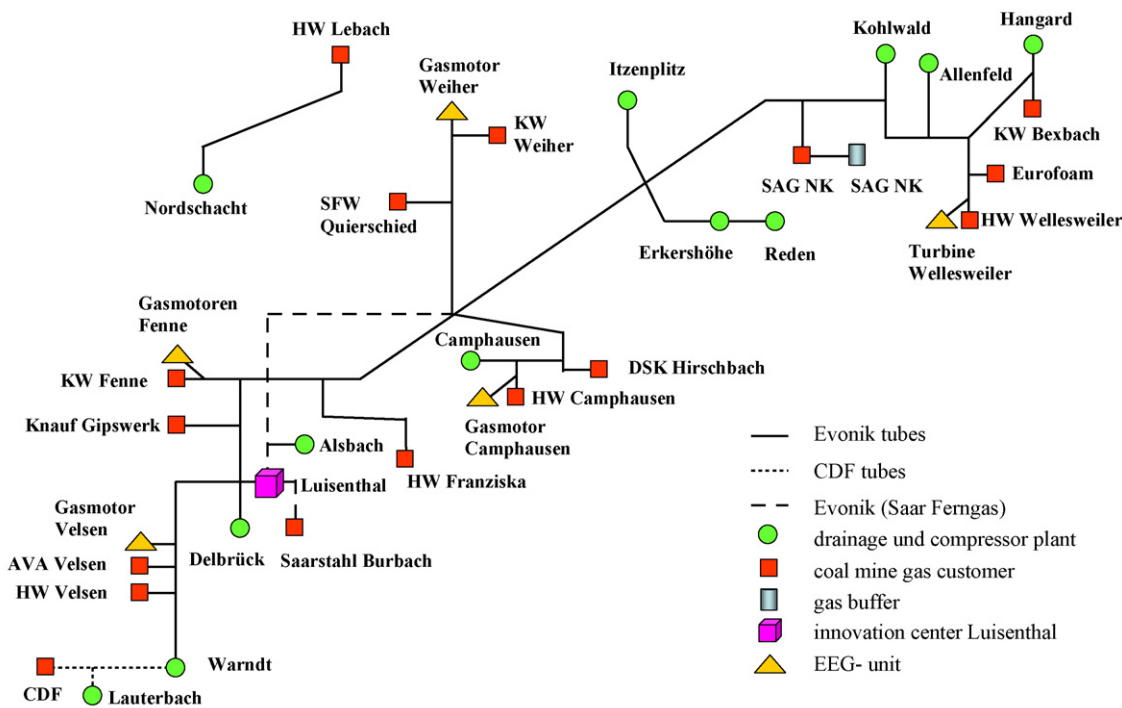


Fig. 1. Coal mine gas network in the federal state Saarland in Germany.

Table 1
Composition of coal mine gas.

25–90 vol.% CH ₄	0.1–10 vol.% O ₂	3–55 vol.% N ₂
2–8 vol.% CO ₂	0.3–1 vol.% C _x H _y	2–300 ppm CO

gas sources with numerous consumers. In Fig. 1, the network with its geographic axial length of approximately 37.5 km between the small villages Warndt and Hangard as well as the different customers are shown.

World wide the coal mine gas network of Evonik has presently one of the highest energy production capacities and therefore it offers an excellent basis for decentralized power generation by means of every kind of lean gases. One of the major characteristics of the coal mine gas network and especially the quality of the used gas in Luisenthal, taken from the network, respectively, is the variability of its composition. The methane concentration was determined by means of micro-gas chromatography. Fig. 2 shows the methane concentrations and their frequency of occurrence within a half-year for the Luisenthal site. This shows that most frequently the methane content is in the range between 40 and 45%.

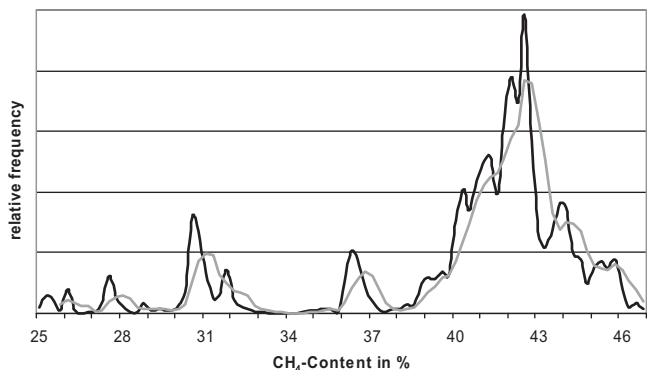


Fig. 2. Relative frequency of the methane concentration at the Luisenthal site.

Fig. 3 shows the time dependent variation in the methane concentration, caused by connection or disconnection of one (or more) gas consumer(s) near the Luisenthal site. These variations can be explained as follows: the local grid segment at the Luisenthal site is mainly fed from two different drainage plants. In this segment there are different coal mine gas consumers (for details see Fig. 1). Because of the demand of the different gas consumers, supplied from the same drainage plants, the flow direction in the gas grid changed because of which the main coal mine gas source, responsible for supplying the Luisenthal site, changed too.

There are other factors, too, that affect the quality of coal mine gas and the methane concentration. In Fig. 4 the methane concentration has been plotted against the air pressure near the Luisenthal site. It indicates clearly the dependence of methane concentration on air pressure. In this context it should be noted that a distinct relationship will be evident only for active coal mine sections.

Another important value of the drained gas is the oxygen content. During the measurement of the methane content in Luisenthal also the oxygen content was measured. It varied between 4 and 6 vol.%.

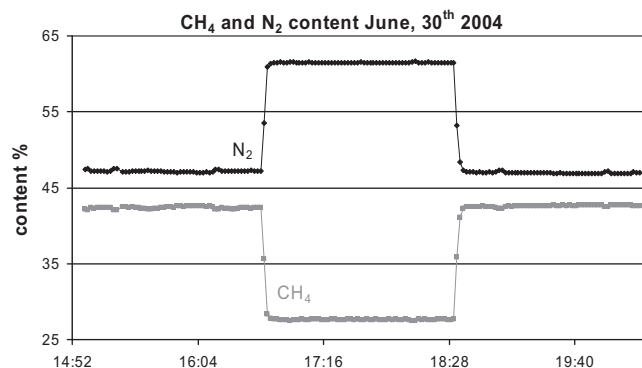


Fig. 3. Dependency of the methane concentration on the gas consumption in the grid nearby the site.

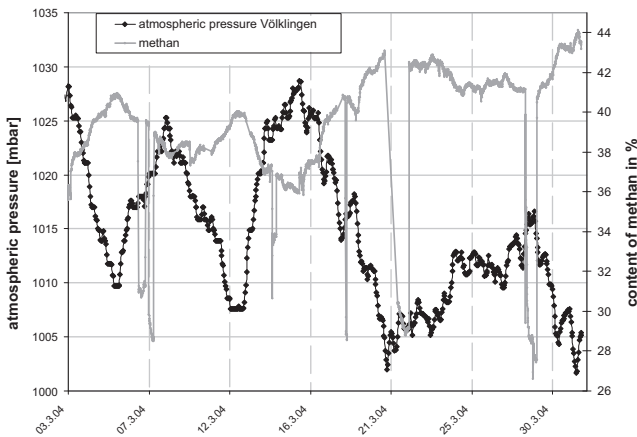


Fig. 4. Influence of the air pressure on the methane concentration.

The maximum content of oxygen can be in the range of approximately 10 vol.%. In that case the methane content is at least 30 vol.%. The lower ignition limit for methane/air mixtures at room temperature is 4.8 vol.%, the upper limit is 16 vol.%, which corresponds to a methane/oxygen ratio of about 1:1. The upper ignition limit increases with increasing temperature [3]. The resulting plots are given in Fig. 5. It is clearly visible, that the most critical coal mine gas composition (means highest oxygen content) has a methane to oxygen ratio of 3:1, which is clearly above the upper ignition range (27 vol.% of methane corresponds to a methane/oxygen ratio of about 1.8:1).

3. Design of the test equipment

The major objective concerning the requirements for the design of the pre-reformer was the usability of the different obtained reformat compositions in the SOFC, independent from the individual compositions of the coal mine gas in Luisenthal. Another objective was to determine the limits for the operational readiness of the pre-

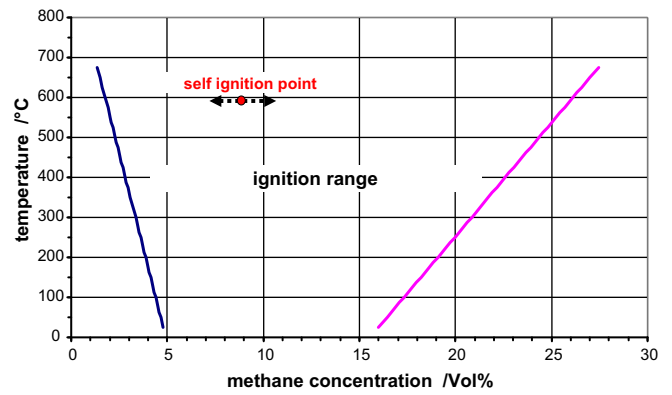


Fig. 5. Higher and lower ignition limit of methane/air as function of temperature.

reformer, especially concerning the broad variations in methane as well as oxygen content and the corresponding effect on the pre-reformer and in a second step on the performance of the fuel cell.

Hence, the design of the test facility for the required tests had to meet a number of requirements, in particular concerning measuring and control instrumentation. The discussed designs, considered and subjected to intensive pre-testing, included separate as well as integrated pre-reformer/SOFC test facilities. The main advantage of two separate test facilities – one for the pre-reformer and one for the fuel cell – is the possibility of an independent control and operation of the two components. The main disadvantage is the double technical effort and high costs, respectively. On the other hand, a full integrated concept has the advantage of less cost, but the efforts for the combined control, etc. are significantly higher, particularly with regard to the rapidly changing methane contents of the used coal mine gas. After having carefully weighed the pros and cons of either concept, the preferred design was a partly integrated system, schematically shown in Fig. 6.

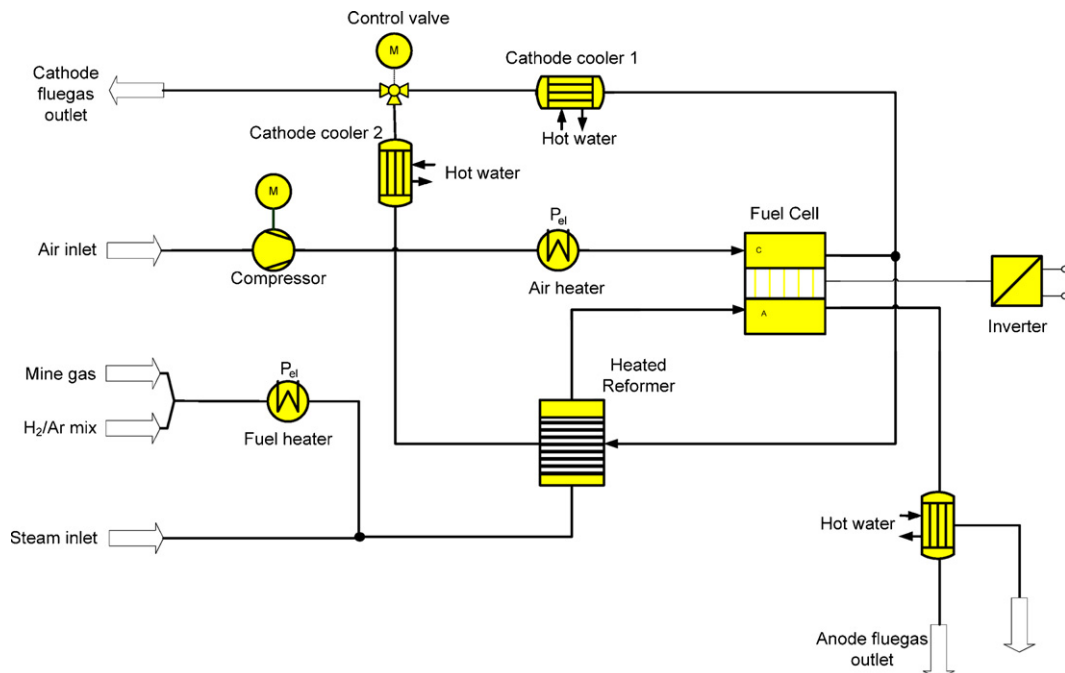


Fig. 6. Design of the test facility.

Table 2
Compositions of simulated coal mine gas.

	Before reforming ^a				After reforming used in stack testing ^b			
	CH ₄ (vol.%)	CO ₂ (vol.%)	N ₂ (vol.%)	O ₂ (vol.%)	H ₂ (vol.%)	CH ₄ (vol.%)	H ₂ O (vol.%)	Ar (vol.%)
MG1	90	7	3	0	29.0	19.5	44.8	6.7
MG2	60	8	27	5	26.6	13.3	36.6	23.4
MG3	30	5	55	10	26.7	4.5	24.9	44.0

^a Steam reforming with S/C = 2.2.

^b CO in the reformat is replaced by H₂ for the stack tests, CO₂ and N₂ are replaced by Ar.

4. Pre-reformer experiments

4.1. Laboratory experiments at Forschungszentrum Jülich

The test program at Jülich was used to evaluate the suitability of the used pre-reformer as well as of the reformat for use in the SOFC. The experimental set-up at Jülich is scaled for a pre-reformer corresponding to a 5 kW_{el} SOFC stack. This requires a certain size of the pre-reformer, in this case ten layers of catalyst. The pre-reformer is a special designed plate type reformer using a plate type catalyst which is the Ni-YSZ SOFC anode substrate of 20 cm × 20 cm with a thickness of 1.5 mm. This material has been proven to work very well as steam reforming catalyst. The reformer is designed for both heated and adiabatic operation. Thermocouples are integrated into two customized units to determine the temperature profile during operation. Typically tests were performed using 0.8 standard liter per minute of methane on each surface of the catalyst plates (means total flow of 16 l min⁻¹). The laboratory experiments were performed using two synthetically composed coal mine gas compositions, mixed with several amounts of CH₄, CO, CO₂, H₂, N₂/Ar and O₂. The compositions, defined in the early beginning of the project, are presented in Table 2. The compositions MG2 and MG3 were used for the pre-reformer testing.

The synthetic coal mine gas was mixed with steam at a steam to carbon ratio (S/C) of 2.2 (because of the low CO and CO₂ content the O/C ratio is comparable) and was preheated to 150 °C to avoid condensation. Addition of steam did not change the methane/oxygen ratio, which meant that the mixture always was above the upper ignition limit. Inside the pre-reformer this mixture was heated to the reaction temperature by the hot air flow, which was passing through the pre-reformer in counter flow, entering at a temperature of about 700 °C. This hot air simulated the off-gas of the SOFC.

Fig. 7 shows the temperature profile in the pre-reformer operated with pure methane as well as the different synthetic coal mine gas compositions. The measurements revealed that the fuel was heated up in the manifold (that is before getting into contact with the catalyst) to a temperature between 350 and 500 °C, depending

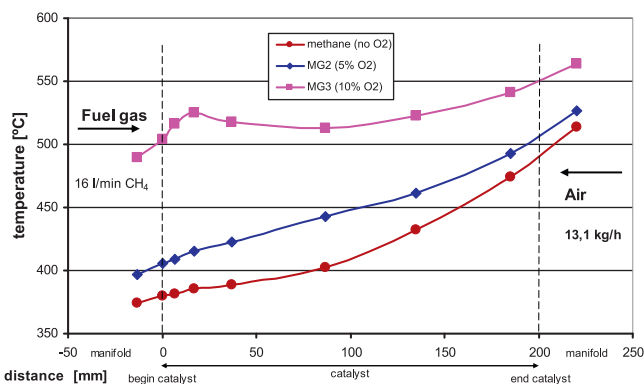


Fig. 7. Temperature profile inside the pre-reformer using different coal mine gas compositions.

on the content of oxygen. The resulting temperatures are clearly below the self-ignition temperature of methane of 595 °C.

Fig. 7 also shows that in case of the reference gas (in this case pure methane) there was only a slight temperature increase at the beginning of the catalyst. As soon as the gas got in contact with the catalyst the steam reforming reaction started and consumed energy, which kept the temperature increase low. There was no decrease of temperature, because at that temperature level the reforming kinetics is quite slow. Because of the exothermic reaction the inlet temperature gets higher with increasing oxygen content, although the effect from zero to 5% of oxygen together with 60% of methane (MG2) was only in the range of 20 °C. The increase up to 10% oxygen combined with a decrease of methane down to 30% (MG3) revealed an increase of more than 100 °C with a further increase at the beginning of the catalyst of another 30 °C. This indicated that the oxidation of methane and hydrogen took place directly when the fuel gas mixture got in contact with the catalyst. This went along with a cooling effect, due to the endothermic nature of the reforming process. After the completed reaction of the oxygen, the temperature increased again by the influence of the heating air flow. However, even with this most critical composition no pre-reformer problems were created.

A micro-gas chromatograph was used to analyze the fuel gas composition at both inlet and outlet. Concerning the simulated coal mine gas compositions the analysis of the pre-reformer products showed that all oxygen was converted completely (below the detection limit) and that part of the methane was reformed to H₂ and CO. The gas composition at pre-reformer outlet is not in equilibrium, which shows that at these low temperatures the reforming kinetics is quite slow. The gas compositions of the educts and products of the pre-reformer are shown in Fig. 8. Hereby, the concept of using a Ni/YSZ cermet to perform steam reforming with oxygen containing coal mine gas has been proven.

Some other operating experiences were gained by changing the air flow using gas MG3. The results for air flow rates of 13.1 kg h⁻¹, 9.3 kg h⁻¹ and 6.3 kg h⁻¹ are given in Fig. 9. The typical oxygen temperature peak in the first part of the catalyst due to the mixed processes of the exothermic oxidation as well as the endothermic reforming reaction was observed in all cases. The temperature pro-

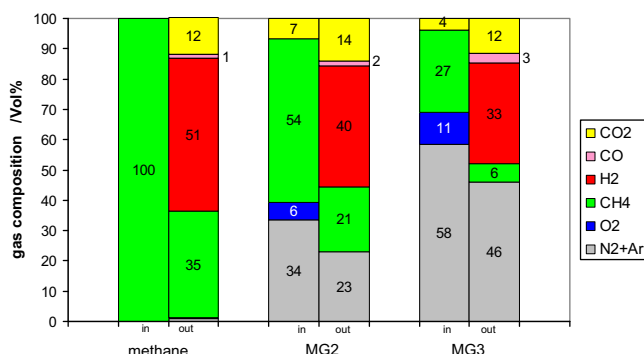


Fig. 8. Gas compositions of the educts and products of the pre-reformer.

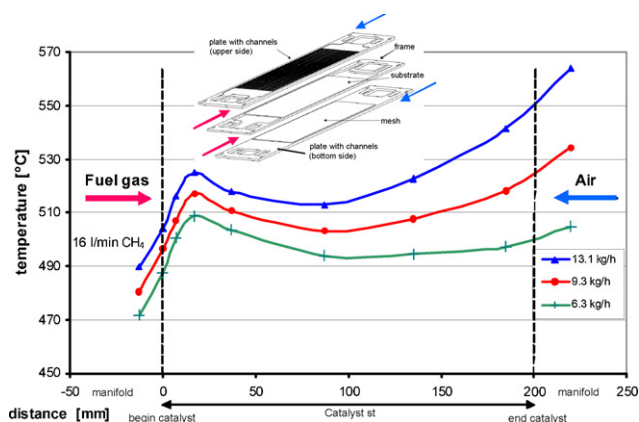


Fig. 9. Temperature profile inside the pre-reformer using different air flow and coal mine gas with 10% of oxygen (MG3).

files suggested that the oxidation took place at the catalyst inlet while the reforming reaction took place more homogeneously over the whole catalyst length.

Reduction of the air flow rate down to 6.3 kg h^{-1} , the fuel outlet temperature was close to the value measured for the pure methane with the higher air flow rate of 13.1 kg h^{-1} (compare Figs. 9 and 10). Thus the air flow rate could be used to control the fuel exhaust temperature depending on the coal mine gas composition.

4.2. Experiments with coal mine gas in Luisenthal

After integration of the pre-reformer in the test facility in Luisenthal, as described in Fig. 6, the monitoring and the scientific follow up was started.

First measurements showed a reforming behavior comparable to the laboratory tests, as shown in Fig. 8. But as can be seen in Fig. 10 (CMG compositions), the temperature profile showed a more pronounced decrease after the first increase because of the reaction with the contained oxygen. Probably this difference was caused by the deviating methane content in the real coal mine gas compared to the assumed simulated compositions MG2 and MG3 used for pre-testing (SG compositions in Fig. 10).

In case of an erratic changeover from a high to a low methane concentration the pre-reformer reacted promptly. The change of the reforming level likewise occurred very fast. Within approximately half an hour, without recognizable time delay, a new balance was reached. Resulting from this, the temperatures in the pre-reformer increased insignificantly about $2\text{--}3 \text{ }^\circ\text{C}$.

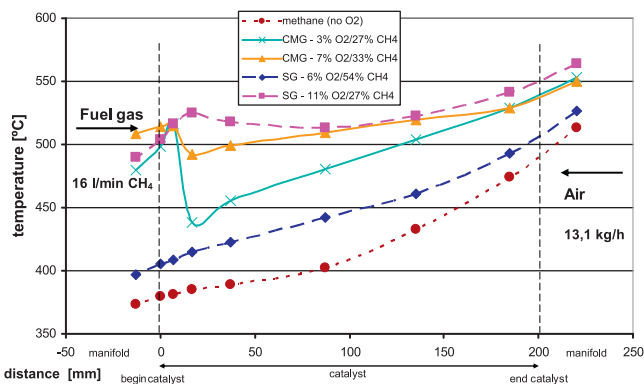


Fig. 10. Temperature profile inside the pre-reformer using different coal mine gas compositions.

4.3. Changes in the reforming behavior during the actual operation time

The evaluation of the measuring data of the pre-reformer in dependence of the actual operation time showed significant changes in the reforming behavior. For the evaluation data after 240, 360 and 1050 operation hours with approximately the same operating conditions were analyzed. In connection with these data the pre-reformer was operated with a methane flow rate of 21.7 sl min^{-1} and a steam mass flow of 1.6 kg h^{-1} . The temperature as measured at the exit of the pre-reformer (see Fig. 10) was taken as reference temperature for the following comparison.

The chosen data showed that the oxygen in the coal mine gas and the higher hydrocarbons ethane and propane were completely converted.

After 240 operation hours, 49.7% of the methane in the pre-reformer were converted to hydrogen, carbon monoxide and carbon dioxide. A small difference in the nitrogen flow rate of $0.004 \text{ mol min}^{-1}$ between entry and exit of the pre-reformer was detected, probably caused by a small leakage from air side to fuel gas side. Referring to a nitrogen content of 79 vol.% in air a nitrogen leakage flow rate of about 6 mmol min^{-1} could be calculated, which corresponds to a leakage air rate of less than 0.1%.

At 360 operation hours there was an aggravation in the reforming behavior in such a way that the methane conversion ratio was reduced to 43.8%. The difference between entry and exit of the nitrogen flow rate increased to 28 mmol min^{-1} , which corresponds to a leakage air rate of about 0.4%.

At the same working conditions the pre-reformer showed a methane conversion ratio of only 35.4% after 1050 operation hours. The difference between in and out-coming nitrogen flow rate increased to 45 mmol min^{-1} , which corresponds to a leakage air rate of about 0.7%.

The comparison of the three data records showed that with increasing operation time the reforming behavior of the pre-reformer became worse. Furthermore the hydrogen fraction of the reformat decreased while the nitrogen fraction in the reformat increased. The decrease of the methane conversion ratio was attributed to the ageing behavior of the pre-reformer.

This was also confirmed by a comparison of the measured composition of the reformat to a simulation. The measured composition and the average temperature of the pre-reformer after 240 operation hours were in agreement with the thermodynamic balance. After 1050 operation hours there was a change in the composition of the reformat in such a way that at the same temperature the status of the thermodynamic equilibrium was no longer achieved. This suggested that during operation the quality of the reforming process decreased. This effect was aggravated by the influence of the leakage air and the herewith joined hydrogen combustion.

A possible reason for the change of the catalytic material could be the formation of nickel oxide at temperatures below $320 \text{ }^\circ\text{C}$, because the kinetics of the steam reforming is still so slow that the oxygen is not completely reacted by the fuel. In this case the oxygen oxidizes the catalyst and affects the process adversely.

5. SOFC experiments

5.1. Laboratory experiments with short-stack

The fuel cell operation tests using simulated reformed coal mine gas were performed on a short stack in the so-called F design [4,5] for planar cells of Forschungszentrum Jülich, in which two anode substrate type cells with double layer $(\text{La,Sr})\text{MnO}_3$ (LSM) cathodes in the size $10 \text{ cm} \times 10 \text{ cm}$ and metallic interconnect plates were used. The short stack was heated, joined and reduced using

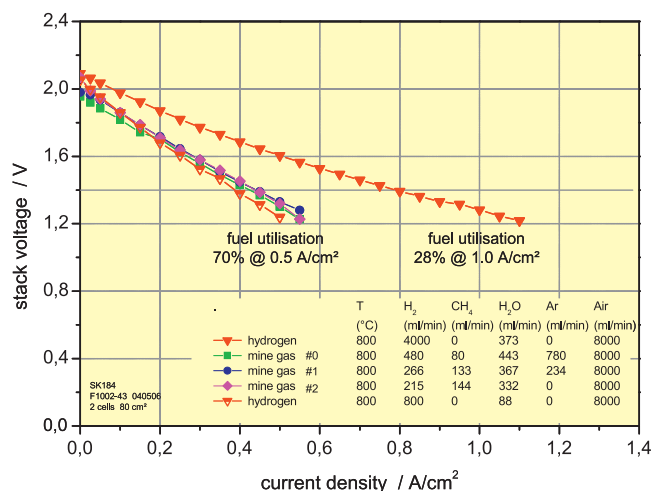


Fig. 11. Current–voltage characteristics of a 2 cell short-stack operated on simulated reformed coal mine gas and hydrogen at 800 °C; cells with LSM cathodes.

standard procedures developed in Jülich. The first characteristic current–voltage measurement was made under standard conditions (800 °C, H₂ + 10 vol.% H₂O as fuel vs. air). The stack was then loaded under these standard conditions with a constant current of 0.3 A cm⁻². It was not supplied with different compositions of simulated reformed coal mine gas until it had operated for a period of 1000 h without any major voltage drops and/or degradation rates. The simulated reformed coal mine gas compositions used for the experiments are listed in Table 2. All measurements were made at a stack temperature of 800 °C.

Fig. 11 shows the current–voltage curves for the three coal mine gas compositions as well as the initial and the final measurement with hydrogen and low fuel gas utilization. For the same volumetric flow rates of the fuel gas, the three different coal mine gas compositions do not give any significant differences in performance. At a voltage of 0.7 V per cell, a current density of approximately 0.44 A cm⁻², i.e. a power density of 0.31 W cm⁻² is achieved. No significant differences between operation with coal mine gas and hydrogen at comparable fuel gas utilization could be observed.

The current–voltage measurements were followed by constant–current operation at 0.3 A cm⁻² using the three gas compositions. The fuel utilization was initially set at 50%, in the final period increased to 70%. Throughout this period of constant current operation only minor variations of less than 10% in the performance (0.22–0.24 W cm⁻²) in dependence of the coal mine gas composition and fuel utilization were observed. More details are reported in [6].

5.2. Laboratory experiments with a 2 kW stack

The results obtained with the short-stack showed, that the targeted 2 kW power for the test on site in Luisenthal could be reached with a stack comprised of 20 cells in the size 20 cm × 20 cm. A first stack, however, did not reach the targeted power level, due to severe leakages in 4 of the 20 layers. The leakages led to an insufficient fuel supply to these layers, giving high power losses in these layers, affecting the total stack power.

With a second stack manufactured and assembled with the same materials for cells and interconnects, measures were taken in the application of the glass–ceramic sealant to prevent the occurrence of leakages. These measures proved to be successful. Current–voltage characteristics were recorded under standard conditions with hydrogen (800 °C, H₂ + 10 vol.% H₂O, air) and with simulated reformed coal mine gas (MG1 in Table 2). At a current–density of 0.50 A cm⁻² a power of 3 kW was reached

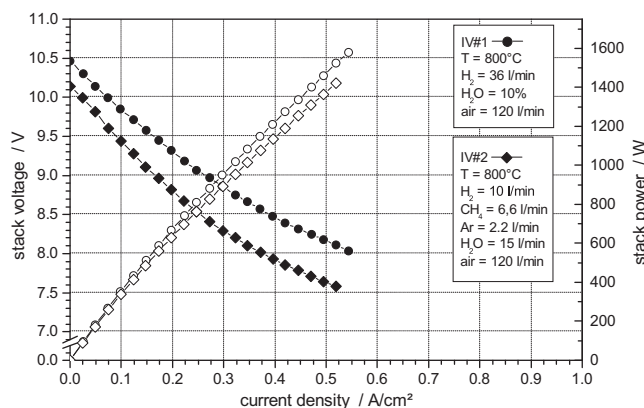


Fig. 12. Current–voltage characteristics of a 10 cell stack operated on simulated reformed coal mine gas and hydrogen at 800 °C, cells with LSCF cathodes.

under hydrogen operation and a power of 2.5 kW under simulated reformed coal mine gas operation. Despite the excellent performance of the stack, it could however not be transferred to the site in Luisenthal. After cooling down the stack showed severe leakages, which for safety reasons prevented the operation outside of a furnace.

A next stack was manufactured and assembled with only 10 cells. To reach the targeted 2 kW power level, cells with the high performance cathode material (La,Sr)(Co,Fe)O₃ (LSCF) were used in this stack. Fig. 12 shows the current–voltage characteristics recorded for this stack operated under hydrogen (IV#1) and under simulated reformed coal mine gas (IV#2). At a current–density of 0.5 A cm⁻² under hydrogen a power of 1.46 kW was reached. Under simulated reformed coal mine gas the power was 1.36 kW. These power levels were lower as expected. It could be observed that individual cell levels suffered from insufficient contacting between the cathodes and the interconnect plates, leading to the lower power of the stack. Nevertheless the stack was operated for a period of over 100 h under simulated reformed coal mine gas at a constant current–density of 0.50 A cm⁻². The stack yielded 1.42 kW (7.96 V at 178 A) in this period. This corresponds to a power density of 0.39 W cm⁻².

In a next phase several parameter variations were conducted, all still with simulated reformed coal mine gas as fuel at a nominal stack temperature of 800 °C. The fuel utilization was raised from 35% to 70%. The current density was varied between 0.3 A cm⁻², 0.4 A cm⁻², and 0.5 A cm⁻². The stoichiometric air ratio (in relation to the converted amount of fuel) was varied between 4, 5 and 6. After each change in one of these parameters the stack was allowed to stabilize for at least 2 h. The achieved stack voltages in dependence of these parameter variations are given in Table 3 and shown in Fig. 13 for comparison with the current–voltage characteristic recorded earlier (IV#2 in Fig. 12). The current–voltage characteristic essentially shows a collection of non–steady–state operation points (except for OCV) since during its recording the stack was never allowed to reach new stable temperature levels.

Table 3

Stack voltages (i.e. power densities) in dependence of the operation parameters: fuel utilization and current densities for operation of the cell stack (20 cm × 20 cm with LSCF cathodes) under simulated reformed coal mine gas.

Fuel utilization	70%			35%
	4	5	6	4
Air stoichiometry in mol/mol				
Current–density in A cm ⁻²	Stack voltage in V			
0.30	7.96	7.99	7.95	–
0.40	7.76	7.63	7.59	–
0.50	7.60	7.53	7.43	7.98

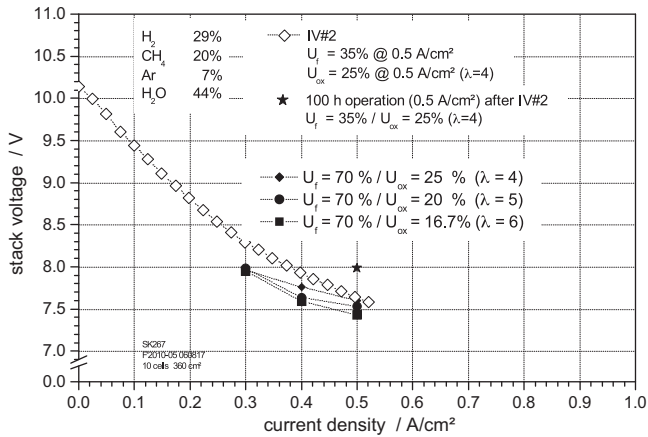


Fig. 13. Current–voltage characteristics of a 10 cell stack operated on simulated reformed coal mine gas compared to the stack voltages reached during variation of the current density, the air stoichiometry and the fuel utilization.

The stack voltages (i.e. stack power) reached during the parameter variations are all lower than obtained during the recording of the current–voltage characteristic, because during the latter the fuel utilization was always lower (and variable). At the lower current–density of 0.3 A cm^{-2} no significant influence of the air stoichiometry value is observed. At higher current densities a higher air stoichiometry results in a lower average stack temperature and thus a lower stack voltage.

After termination of the operation and cooling down of the stack the leakage test showed a sufficient gas tightness of the stack to allow for the transfer to Luisenthal to perform an on-site test with coal mine gas.

5.3. Experiments with coal mine gas in Luisenthal

The stack was mounted in the test facility next to the pre-reformer unit. During heating to operating temperature with hot air the anode compartment of the stack was flushed with 4% hydrogen in nitrogen to prevent the Ni in the anode from re-oxidation. Already during this phase several cells in the stack showed a much too low OCV, indicating again leakages. Nevertheless coal mine gas was supplied to the stack for a few hours during which current was drawn from the stack. At the time of the test the methane content of the coal mine gas was about 46 vol.%. The average stack temperature was about $840 \text{ }^\circ\text{C}$. At a current of 66 A the stack voltage was still 8.1 V, giving a power of 0.53 kW, even with several cells having a cell voltage close to zero. The operation of the stack had to

be aborted after a few hours, because the temperature in the fuel exhaust line of the stack reached values above the safety limits. Most likely the much higher pressure difference between the fuel and the air feed to the stack in the test facility at Luisenthal caused severe failure of the glass–ceramic sealants in several levels of the stack.

Still, if only for a few hours, an SOFC stack was operated on a lean coal mine gas directly supplied to the stack from its natural source, showing the capability of the SOFC-technology for efficient electricity production from coal mine gas.

Until 2009 Jülich has developed a stack with a power of 1 kW which showed more resistance to thermal stresses. Hence it has been decided to start a new on site experiment to collect more information about the behavior of the SOFC with coal mine gas. In this experiment, it was possible to achieve about 131 operating hours in total including two thermo-cycles down to ambient temperature. During this period the fuel cell operated for 62 h continuously. This period was considered as the basis for the evaluation of the SOFC performance. The coal mine gas had a methane content of 28 vol.% on average.

The fuel cell was operated at constant stack voltage. The current density varied between 80 mA cm^{-2} and 160 mA cm^{-2} only, because the stack could not reach the nominal operation temperature because of special restrictions within the test bench. During operating hour 22, a decrease of the current density happened caused by a lower air inlet temperature. During night the plant was not observed and therefore the temperature has been lowered to protect the fan from excessive heating. A second drop of current density has been noticed during operating hour 31. The voltage of the load device increased; this led to loss of current. A power breakdown caused the negative peak during operating hour 47. The remaining trend correlates with temperature. The stack operating temperature was planned to achieve $780 \text{ }^\circ\text{C}$. At the end of the experiment, only $700 \text{ }^\circ\text{C}$ have been reached. Because of this low temperature a power of only 420 W was produced (Fig. 14).

Unfortunately the field test had to be aborted due to a technical defect in the test facility. However, a new test is planned in order to reach the optimal operating temperature and higher power output.

5.4. Comparison of the synthetic and real coal mine gas test results

In reference to the laboratory results and taking into account the much lower operation temperature during the tests with real coal mine gas the performance was comparable.

With synthetic gas the stack efficiency was 42%, related to hydrogen at 70% fuel utilization and 750 mV cell voltage. During

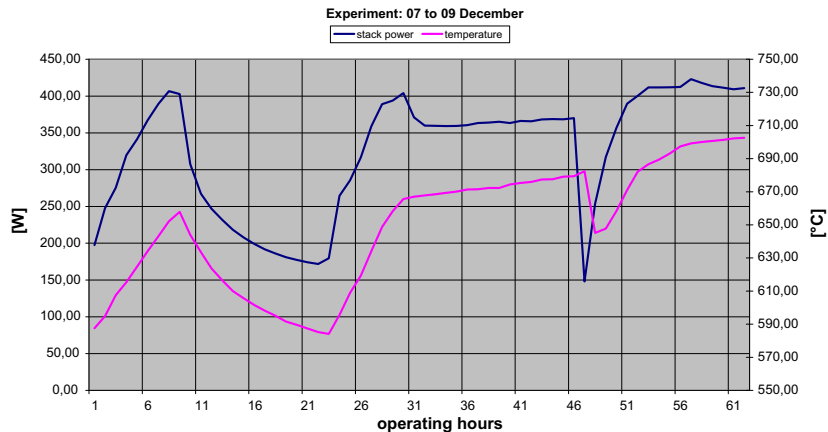


Fig. 14. Power of a 10 cell stack with 1 kW maximum power operated on coal mine gas in Luisenthal.

the relatively short operation with real reformat the fuel utilization was much lower and so the efficiency was lower. Due to a technical defect in the test facility, no long-term test with real coal mine gas was performed.

6. Conclusion and future prospect

The project “Development of a Solid Oxide Fuel Cell (SOFC) for the Utilization of Coal Mine Gas” was essentially successfully finished by the partner consortium Evonik New Energies GmbH (former STEAG Saar Energie AG), Forschungszentrum Jülich GmbH and the IZES gGmbH. Within the project both the pre-reformer and the SOFC based on the Jülich technology were operated for the first time outside the laboratory under real conditions. The experiments were evaluated regarding the characteristics long-term stability, dynamic behavior and ageing.

The pre-reformer fulfilled completely the expectations with approximately 1700 operating hours. It was examined in particular regarding its dynamic behavior with varying methane contents at different boundary conditions. Even after this long operation period the pre-reformer is ready for further use, even though some degradation of the catalyst occurred.

During the time of the project, a total of five kW_{el}-class fuel cell stacks were manufactured in Jülich, commissioned and characterized there on laboratory conditions. The synthetic coal mine gas used for these experiments was made from different clean gases according to real conditions in Luisenthal. One of the fuel cell stacks was installed into the experimental facility in Luisenthal and operated for about 130 h under real conditions with coal mine gas. The performance data were appropriate on what one could expect after the commissioning in the lab. Due to restrictions in the test bench the nominal operating temperature could not be achieved and so

the power output was lower than planned. After improvement of the equipment the test will be continued.

As important result one has to note that the pre-reformer manufactured in Jülich, the fuel cell and not least the plant concept – which was conceived together with all partners – are suitable for operation with coal mine gas, in particular regarding the temporary concentration variations of methane between approximately 30% and 45%.

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