Investigation of SOFC operation with steam gasifier product gases as a basis for enhancing its performance

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Abstract

Solid oxide fuel cells (SOFC) represent a promising technology to increase the electrical efficiency of biomass-based combined-heat-power systems in comparison to state-of-the-art gas engines, additionally providing high temperature heat. To identify favorable gas compositions and operating conditions for an efficient coupling with gasifiers at low degradation risk is of major importance to ensure stability, reliability and durability of the systems used. Therefore, this study presents a comprehensive analysis on the influence of main gas components on the performance of an industrial-size SOFC relevant for the use with product gases from biomass gasification. Recommendations for concentrations of H_2O, CO, CH_4 and CO_2 in a H_2+N_2 gas mixture for enhancing cell performance are presented. Moreover, the degradation stability of a loaded cell fueled with a modeled steam-gasifier product gas is investigated showing no performance- or substrate degradation.

1. Introduction

Gasifiers coupled with gas engines increasingly replace steam turbine cycles as state-of-the-art systems for converting solid biomass to power because they provide higher thermodynamic efficiencies, especially for small- to medium-scale plants. However, also in this case, the electrical efficiency is limited by the thermodynamic cycle. Combined with high prices for biomass feedstocks, this reduces the attractiveness of electricity production from biomass. Coupling gasifiers with high temperature SOFCs instead of gas engines would increase the electrical efficiency from around 30% to values up to over 40%, in addition to providing high temperature heat and therefore increasing the attractiveness of power production from solid biomass. [1]

As SOFCs are based on heterogeneous catalytic reaction processes, the main drawback of their use with gasifiers in comparison to combustion engines is the higher sensitivity to degradation. This is caused by the components of the derived product gas, which includes impurities like tars, dust, sulfur- and chlorine compounds that can act either as catalyst poison or lead to depositions in the porous fuel electrode, deteriorating SOFC performance [2]. SOFC operating conditions like temperature, electrical load, but especially the concentration of the main components of the employed fuel gas can also induce fuel electrode degradation, e.g. a low steam-to-carbon ratio (SCR) can lead to carbon deposition and a high steam concentration to re-oxidation of the nickel catalyst used in state-of-the-art SOFC anode substrates [3]. To investigate

favorable gas compositions and operating conditions for an efficient coupling of SOFCs with gasifiers at low degradation risk is of major importance to ensure stability, reliability and durability of the systems used.

1.1. SOFC operation with gas components from a product gas

Several studies have already been published investigating the influence of main gas components of biomass gasification product gases on SOFC characteristics. It is argued in [4], that in case of CO/H_2 mixtures, a performance decrease of an anode-supported cell (ASC) with nickel/yttria-stablizied zirconia (Ni/YSZ) anode and 25 cm^2 active surface can be observed at high CO fractions (>90 vol%). In [5], the impact of bio-syngas and its components on the anode of a nickel/gadolinium-doped ceria (Ni/GDC) electrolyte-supported cell (ESC) is investigated with the outcome that increasing amounts of N_2 and CO in dry H_2 lead to an increase of diffusion losses and therefore a decrease in cell performance. However, the addition of CO_2 to dry H_2 leads to the production of H_2O according to the water gas shift (WGS) reaction (1). As H_2O is the product of the hydrogen oxidation reaction (2), even small amounts of water decrease the voltage losses at low electrical load (activation polarization), thus linearizing the current-voltage correlation of a SOFC, as experimentally shown in [6] and theoretically described in [7]. This linear current-voltage correlation results in a more stable operation behaviour due to better controllability of the cell.

$$CO + H_2O \Leftrightarrow CO_2 + H_2 \qquad (1)$$

$$H_2 + 0.5O_2 \Rightarrow H_2O \qquad (2)$$

The results of a detailed electrochemical characterization of a Ni/YSZ ASC with 25 cm^2 active surface over a broad measuring range of temperature and hydrogen/carbon/oxygen-ratios of the fuel is presented in [8]. The authors claim that although kinetic parameters for the oxidation of H_2-CO-CO_2-N_2-H_2O mixtures are the same as for pure H_2 operation, only H_2 is directly electrochemically oxidized in a Ni/YSZ SOFC. The opposite is claimed by the authors of [9]. In this work, the role of CO and CO_2 on the performance of a Ni/YSZ ASC with 10 cm^2 active surface is investigated with the outcome that the electrochemical reactivity of CO is comparable to H_2 as long as the amount of fuel in a fuel/N_2 mixture does not exceed 27 vol%. Higher CO concentrations would decrease the cell performance due to higher diffusion losses of CO in comparison to H_2.

In [10] it is also highlighted that a higher performance for the oxidation of H_2 than of CO can be achieved in Ni/YSZ anodes. Moreover, the importance of the WGS reaction was highlighted, as in H_2-CO mixtures the produced H_2O (reaction (2)) reacts with CO to form H_2 as long as the H_2 content is greater than ca. 50 vol%. The higher diffusion resistivity of CO in comparison to H_2 is also claimed as a reason for a lower oxidation rate of CO in [11]. In [12], the cell performance as well as polarization losses of a Ni/YSZ ASC with 25 cm^2 active surface was investigated when using $CO/CO_2/N_2$ and $H_2/H_2O/N_2$ mixtures revealing lower performance levels when using CO as oxidant. A more comprehensive study on the influence of varying mixtures of H_2, H_2O, CO, CO_2, CH_4 and N_2 on the current-voltage correlation of a Ni/YSZ button cell was conducted by [13] to develop a black box model of the cell, however, without a detailed description of the loss mechanisms.

Summing up, the literature review revealed that H_2 is a more preferable oxidant than CO due to better diffusivity and electrochemical reactivity. Moreover, dilution with N_2 and CO_2 should be

minimized to avoid an increase of diffusion losses for all reactive gas components to the active centers of the substrate. Furthermore, the importance of the WGS reaction was highlighted as CO_2 would shift the water gas equilibrium to a side where more CO than H_2 will be formed, thus increasing losses due to worse electrochemical activity. However, in dry H_2-CO_2 mixtures H_2O can be formed via WGS reducing the activation polarization, thus linearizing the current-voltage correlation of a SOFC.

1.2. Coupling gasification and SOFCs

Anode substrate: The literature review revealed that in general cells with Ni/GDC or Ni/YSZ substrate have been investigated for the use with product gases relevant for biomass gasification. Significantly more publications deal with cells based on Ni/YSZ anodes, possibly due to their better performance in electrochemically oxidizing hydrogen and being closer to a broad commercialization [3]. However, as comprehensively reviewed in [2] and [14], cells with Ni/GDC anode show the highest potential for the use with bio-syngases due to their higher tolerance against contaminants like H_2S and HCl in comparison to cells with Ni/YSZ anode. Moreover, this anode substrate is less prone to the formation of solid carbon deposits when fuelled with carbonaceous gases, especially at a low SCR [15]. Thus, cells with Ni/GDC anode were used for the experiments presented in this paper, especially considering future experiments with fuel gases containing contaminants as well as real product gases from biomass gasifiers.

Cell design: Moreover, the differences in the structure of the layers between an ESC and an ASC as shown in Figure 1 have to be considered to find a suitable design for the use with bio-syngases. In an ASC, most of the mechanical support is applied by the anodic substrate. Thus, the risk for gas leakages from the cathode to the anode side through cracks and therefore cell malfunction induced by anode degradation is higher for ASCs than for ESCs. Degradation can result from solid carbon depositions or forming of nickel oxide. This has to be considered when cells are operated in environments favouring carbon deposition or nickel re-oxidation, both possible when using product gases from biomass gasification.

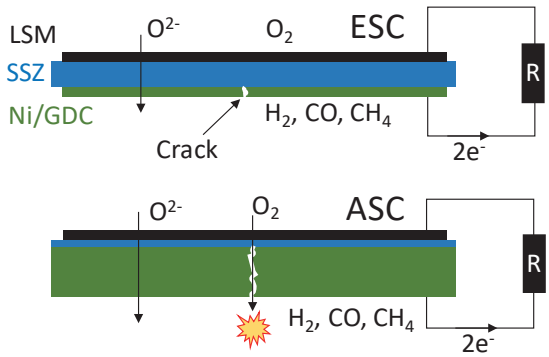


Figure 1 Comparison of ESC (top) and ASC (bottom) SOFC structure

To increase the relevance of test results for industrial applications, the use of cells with an active surface of at least 80 cm^2 is beneficial as macroscopic effects like uneven gas and temperature distribution and furthermore fuel utilization can be reproduced more easily.

Gasifier, gasification agent and gas cleaning: Considering gasifier technologies, there are big differences in product gas compositions depending on feedstock, operating conditions and gasification agent. Table 1 shows examples of typical product gas compositions from common gasifier designs, both having high potential for the coupling with SOFCs [16]: a fixed-bed downdraft gasifier with air (FDA) and a fluidized bed gasifier with steam (FBS) as gasification agent.

vol% w.b.	FDA	FBS
H_2	16	24
H_2O	15	37
CO	17	15
CO_2	13	13
CH_4	3	7
N_2	36	4
SCR	0.75	1.68
H_2/CO	0.94	1.6
LHV [MJ/Nm^3 w.b.]	4.6	6.5

Table 1 Product gas compositions of common gasifier designs (values based on [17], [18], [19] and internal data)

To find out the most promising gasifier type for the experimental investigations, the following issues were considered: The lower heating value (LHV) of the FBS gasifier product gas is higher than that of a FDA gasifier. Besides, considering the higher H_2/CO ratio of the FBS gasifier and the before mentioned better reactivity of H_2 in comparison to CO, a better performance can be expected. Moreover, the significantly lower N_2 content is supposed to result in a lower diffusion resistivity of the reactants to the anode. Finally, due to the higher SCR, solid carbon depositions in the anode substrate can be avoided [20] as carbon reacts with steam to form H_2 and CO according reaction (3). Nevertheless, high steam contents might lead to re-oxidation of the nickel catalyst (reaction (4)), resulting not only in a decrease of active sites and therefore performance losses but also in the growth of nickel grains resulting in mechanical substrate degradation. This degradation behaviour is described in [21] for a direct coupling of a SOFC with a gasifier as well as theoretically in [22].

$$C + H_2O \Leftrightarrow H_2 + CO \qquad (3)$$

$$Ni + H_2O \Leftrightarrow H_2 + NiO \qquad (4)$$

Furthermore, a hot/dry gas cleaning is suggested as the most promising, which improves the system efficiency avoiding steam condensation as shown for the FDA case in an Ni/YSZ ASC SOFC in [16]. With this cleaning option, all contaminants beside tars could be removed. Besides, literature suggests that cell degradation can be avoided with the expected tar concentrations for cells with Ni/GDC anode [2]. Nevertheless, the high steam content of a FBS producer gas with hot/dry gas cleaning can be as well a risk for the cell as stated in [16].

Summing up, to the best of the authors' knowledge a comprehensive study on the influence of main gas components (H_2, CO, CH_4, CO_2, H_2O, N_2) on the performance of an industrial-size SOFC relevant for the use with product gases from biomass gasification is missing in literature. Therefore, this work deals with the results of an electrochemical characterization of a Ni/GDC ESC when using synthetic fuel gas mixtures with generally high amounts of water vapor, as product gases from steam gasifiers seem to be most promising for the use with SOFCs. Moreover, the possible risk of degradation caused by fuel electrode re-oxidation in a steam-rich atmosphere is evaluated. The obtained results will enable defining advantageous operating conditions in order to achieve an efficient coupling of gasifiers with SOFCs whilst avoiding cell degradation.

2. Materials and methods

An industrial-size ESC SOFC with 80 cm^2 active surface was used for the experimental investigations. The cell consisted of a 40 µm Ni/GDC anode and a 45 µm lanthanum strontium manganite (LSM) cathode on both sides of an 165 µm electrolyte out of scandia stabilized zirconia (SSZ), manufactured by IKTS [23].

The cell was placed in an alumina housing developed in-house with nickel- and platinum meshes used for the electrical contacting of anode and cathode. This

assembly enables electrochemical impedance spectroscopy (EIS) measurements with minimal cross influences from the periphery to ensure accurate representation of cell characteristics. The cell holder was placed in a test rig shown in Figure 2, which enabled fuelling the SOFC with dry or humidified gas mixtures.

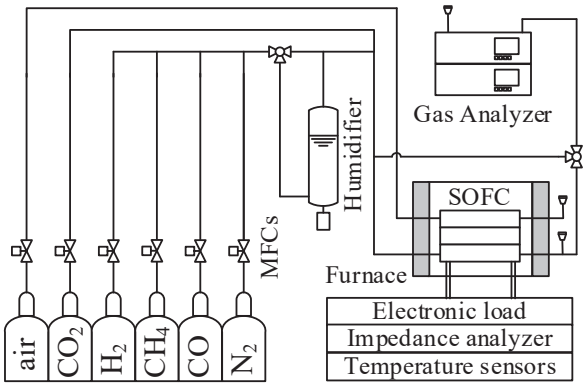


Figure 2 Test rig scheme based on [12]

Current-voltage curves as well as EIS measurements were conducted using a Bio-Logic SAS SP-150 analyser. A Bio-Logic SAS VMP3B-80A/3V booster was used to perform experiments up to 80 A electrical load. The maximum load was restricted by a minimum cell voltage of 0.7 V. At higher loads nickel re-oxidation is thermodynamically possible due to a sufficient high oxygen partial pressure at the anode, as described in [24]. The frequency range for EIS measurements was varied between 100 mHz and 10 kHz with a current amplitude increasing with the DC-current load. Temperatures on the anode side were recorded in the centre and the border area of the flow field at 3 points along the flow direction within the alumina housing, therefore not representing a punctual but an area-averaged cell temperature for each measurement point. Moreover, a continuous off-gas and temporary feed-gas analysis was conducted using an ABB Advanced Optima 2000 gas analyzer with a Uras 14 and Caldos 17 module. To investigate microstructural phenomena, post-mortem analyses were performed with a Zeiss Ultra 55 equipped with a field emission scanning electron microscope (SEM) and an energy-dispersive X-ray spectroscope (EDX).

To investigate the influence of gas components on the cell performance, each component was varied as shown in Table 2 at 850°C regulated oven temperature and 2 slpm anodic and cathodic gas flow rates. The variation of the N_2 compound is neglected in this paper due to less relevance for FBS systems in comparison to FDA systems. Moreover, it is generally known that an increase of the nitrogen compound leads to a performance decrease due to a lower LHV of the fuel gas and higher diffusion losses for the reactive species to the active centres as described in [6]. To investigate the influence of carbonaceous species on the cell characteristics, the N_2 content of a reference mixture containing 50 vol% H_2, 25 vol% H_2O and 25 vol% N_2 was replaced by CO, CH_4 and CO_2 thus simulating steam gasifier product gases and enabling WGS- as well as Methane-Steam-Reforming (MSR) reactions (5) in comparable extents.

$$CH_4 + H_2O \Leftrightarrow CO + 3H_2 \qquad (5)$$

At each operating point, a detailed electrochemical analysis was conducted by means of current-voltage curves as well as EIS at open circuit voltage (OCV) and several load levels. Temperatures on the anode side within the ceramic cell holder were measured at OCV, full-load and intermediate load after a stabilization period.

ID	850°C 2 slpm	H_2	H_2O	CO	CH_4	CO_2	N_2	LHV MJ/Nm³
		vol%						
1	Influence H_2O	50	5				45	5.54
2		50	10				40	5.54
3		50	25	Reference			25	5.54
4		50	50					5.54
5	Influence CO	50	25	5			20	6.17
6		50	25	10			15	6.79
7		50	25	25				8.68
8	Influence CH_4	50	25		5		20	7.33
9		50	25		10		15	9.12
10		50	25		25			14.49
11	Influence CO_2	50	25			15	10	5.54
12		50	25	5		15	5	6.17
13		50	25		5	15	5	7.33
14		50	25	5	5	15		7.96
15	FBS 800°C	22	36	11	5	11	15	5.61

Table 2 Operating points of parameter study (ID1-14) and long-term experiment (ID15)

To analyse changes in the cell performance for each gas composition, the following four parameters were compared between the operating points. Except for the OCV, all comparison parameters were taken at a constant current density of i = 300 mA/cm² representing a high load for all supplied gas compositions (see Figure 4):

- The cell voltage U as an indicator for the electrical power output as well as the OCV representing the electrochemical potential for the applied gas mixture.
- The area specific resistance (ASR) representing the sum of all voltage losses within the cell according to equation (6) [7].

$$ASR = \frac{OCV - U}{i} \; [\Omega cm^2] \qquad (6)$$

- The electrical efficiency η_{el} according equation (7).

$$\eta_{el} = \frac{U * i * ActiveSurface}{\dot{V}_{Anode} * LHV_{Mixture}} \; [\%] \qquad (7)$$

- A parameter defined by the authors as conversion efficiency η_{conv} according equation (8), which is assumed to represent the efficiency of the cell for converting chemical energy in electrical energy neglecting spare fuel by considering the fuel utilization U_f. This parameter enables to compare cell performances between different fuel-gas energy contents.

$$\eta_{conv} = \eta_{el} \frac{1}{U_f} \; [\%] \qquad (8)$$

In addition to experiments with varying fuel gas composition the cell was run on a simulated product gas from an in-house FBS gasifier at a lower temperature of 800°C for 500 h. The gas composition is shown as ID15 in Table 2. The higher N_2 content in comparison to the FBS mixture presented in Table 1 results from pressurizing the fuel tank with N_2 necessary for the operation of the in-house FBS gasifier. A constant load of 300 mA/cm² was applied and current-voltage-curves as well as EIS-spectra were recorded every 2 hours to track the degradation behavior as a result of possible nickel re-oxidation within the anode substrate in this steam-rich environment. Afterwards, SEM and EDX analyses were conducted to investigate changes in the anode substrate.

3. Results and discussion

In Figure 3, the abovementioned parameters U, OCV, ASR, η_{el} and η_{conv} are illustrated for the following operating conditions: current density of 300 mA/cm² (except OCV), gas compositions as shown in Table 2, 850°C regulated oven temperature and 2 slpm for both anodic and cathodic gas flow rates. Furthermore, Figure 4 shows current-voltage correlations for the reference gas mixture and mixtures without N_2. A parameter analysis was performed to reveal recommendations for gas compositions to increase cell performance. A thorough explanation of the specific loss mechanisms considering impedance data would exceed the scope of this paper and is therefore only briefly discussed.

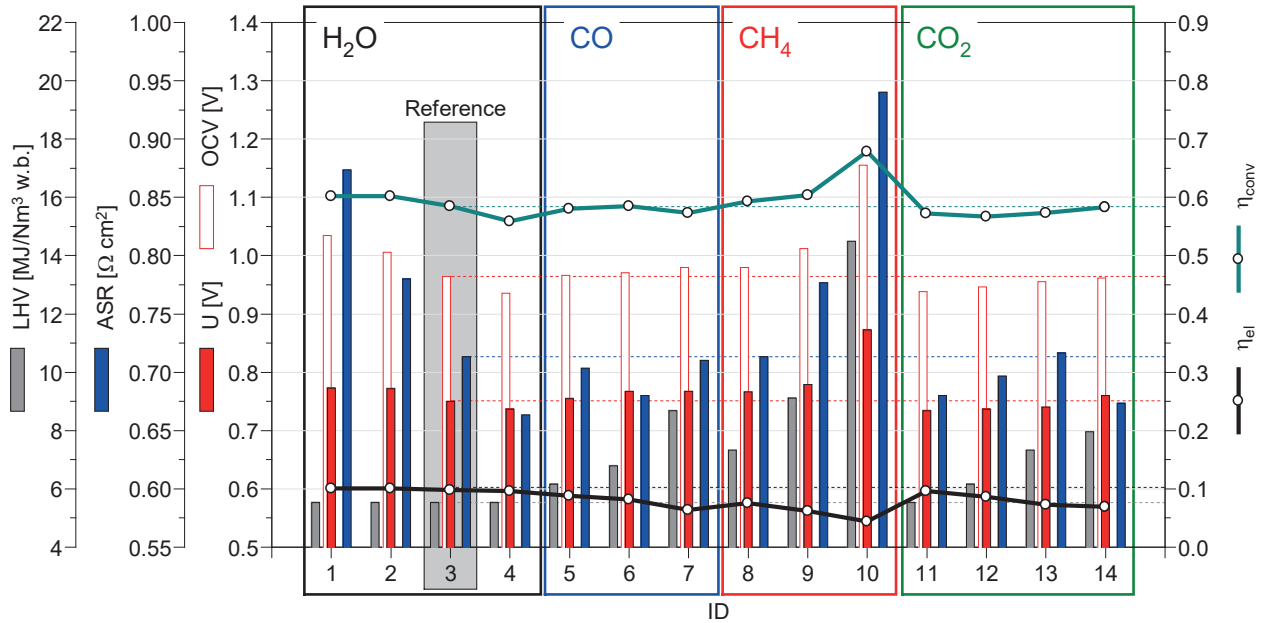


Figure 3 U, ASR and efficiencies at 300 mA/cm² electrical load and OCV

H_2O: The steady decrease of the cell voltage can be explained as follows: Higher concentrations of H_2O, which is the reaction product of the hydrogen oxidation reaction (2), lowers the OCV and therefore leads to a decrease of cell voltage despite constant LHV as shown in Figure 3. However, the increasing water content from 5 to 50 vol% leads to a strong decrease of the ASR due to lower voltage losses at low load levels (activation polarization), which is also described in [6]. A decrease of voltage losses is in general desirable for an efficient operation of SOFCs. Nevertheless, considering the before mentioned necessary comparability of the reference gas mixture to a FBS gasifier product gas, a mixture of 50 vol% H_2 and 25 vol% H_2O in N_2 is employed as reference mixture for further experiments, whereas N_2 will be substituted by carbonaceous species. This mixture shows the best comparability to FBS product gases at a passable cell performance reduction.

CO: Increasing the CO concentration in the reference gas mixture results in an increase of the fuel-gas LHV and moreover the cell voltage at decreasing ASR. However, no voltage increase can be observed between 10 and 25 vol% CO, despite constantly increasing LHV. At a certain CO concentration above 10 vol% (H_2/CO ratio smaller 5), it seems that CO electrochemically oxidizes before taking part in WGS reactions (1) to form electrochemically more reactive H_2, resulting in an increasing ASR. Therefore, also considering the peak of η_{conv} at 10 vol% CO, substituting N_2 of the reference gas mixture with CO concentrations higher 10 vol% should be avoided.

CH_4: In comparison to an increasing CO concentration, an increase of CH_4 concentration results in a 3 times higher H_2 production rate when comparing WGS reaction (1) with MSR reaction (5). The obtained higher volume flow and therefore lower fuel utilization in combination with a higher H_2 concentration within the cell results in an increase of the OCV [7]. Nevertheless, the ASR increases with increasing CH_4 concentration, leading to a stronger decrease of electrical efficiency. This can be argued as a result of a measured temperature decrease of ca. 15 K from fuel inlet to fuel outlet due to endothermic MSR reactions (5). A

decrease in temperature results in a higher ohmic resistance of the electrolyte according to [7], which could be confirmed by analyzing impedance data. Considering the nearly full conversion of CH_4 into CO and H_2 measured with the gas analyzer, no water will be left in the gas when the electrochemical oxidation of H_2 takes place. This leads to a higher activation polarization as described in the introduction chapter. As a result, the current-voltage curve for ID10 at 25 vol% CH_4 loses its linearity as shown in Figure 4. In conclusion, a H_2O/CH_4 ratio higher than 1 is strongly recommended to avoid high polarization losses and ensure linearity of the current-voltage correlation.

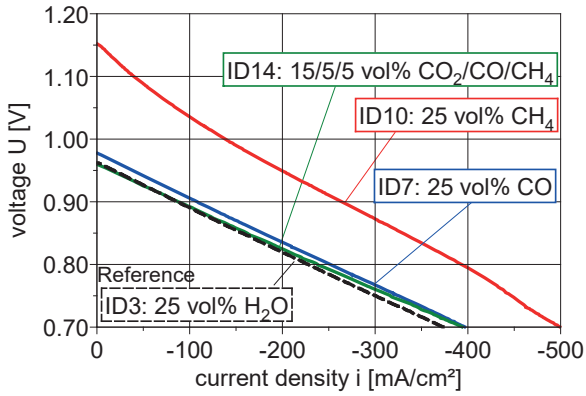


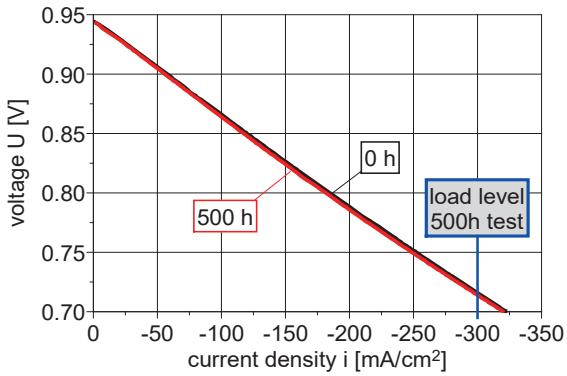
Figure 4 Current-voltage correlations of gas compositions without N_2

CO_2: When adding 15 vol% CO_2 to the reference gas mixture, a fraction of CO_2 reacts via WGS with H_2 to produce H_2O and CO. As described in the introduction chapter, CO has a lower electrochemical activity than H_2 explaining the voltage decrease, also lowering the OCV. This also might explain the ASR decrease. When adding the reactive species CO and CH_4 even in small extents of 5 vol%, this negative impact gets partly compensated. Nevertheless, voltage measured while feeding the anode with gas mixtures of 5 vol% N_2 (ID7: 10 vol% CO or ID10: 10 vol% CH_4) is not achievable when using gas mixture ID14, despite a lower ASR. For this reason, it can be concluded that the amount of CO_2 in the gas mixture should always be as low as possible, especially to avoid conversion of electrochemically high-reactive H_2 with CO_2 to CO and H_2O via WGS and to keep diffusion resistances low for electrochemically active species.

Considering the results of the parameter study, the gas composition of an in-house FBS gasifier fueled with wood pellets presented as ID15 in Table 2 is confirmed as suitable for the use as fuel gas for the 500 h degradation experiment due to following reasons:

- It shows a comparable composition to the FBS mixture presented in Table 1, besides a higher N_2 concentration thus lowering the power output but not influencing WGS and MSR reactions.
- The steam content of 36 vol% shows a risk for degradation due to nickel re-oxidation (4) according to [21] which is relevant to investigate for industrial applications. Nevertheless, it is far below 50 vol% to avoid a strong ASR increase and therefore higher polarization losses as well as it ensures a H_2O/CH_4 ratio higher than 1.
- Although the H_2/CO ratio of 2 is smaller than 5, which was not recommended before, the higher H_2O content might also increase WGS reactions and therefore a higher production rate of H_2 from CO and H_2O. Besides, it is a much more favorable ratio than for FDA gasifiers (see Table 1).

Long term test with typical composition of FBS: In Figure 5, the results of the 500 h experiment at 800°C oven temperature and 300 mA/cm^2 with simulated product gas from an in-house FBS gasifier (see Table 2 - ID15) are presented. Current-voltage curves as well as impedance spectra show no degradation of the cell performance.



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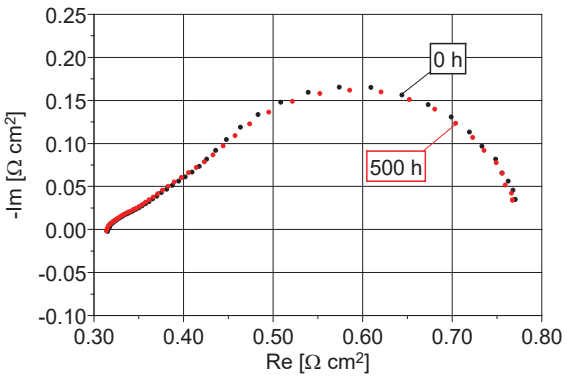
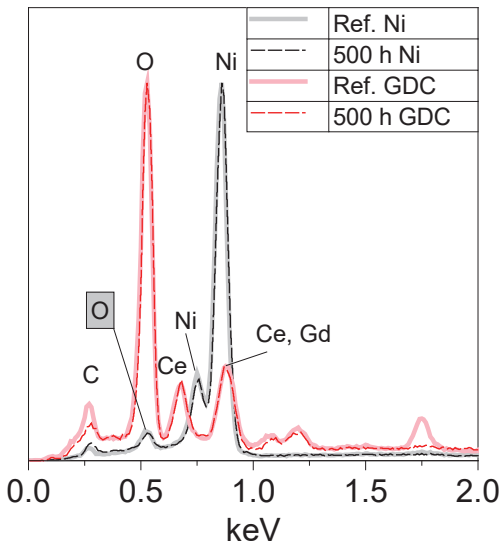


b)

Figure 5 a) Current-voltage curves and b) impedance spectra comparison of cell before and after 500h long term experiment

Nevertheless, performance degradation analyses do not deliver information about possible local changes in the microstructure of the anode substrate, which could cause a fast cell degradation after longer operation periods. Therefore, SEM and EDX analyses were used to investigate if the anode structure changed during the operating time. The results of these analyses are presented in Figure 6.



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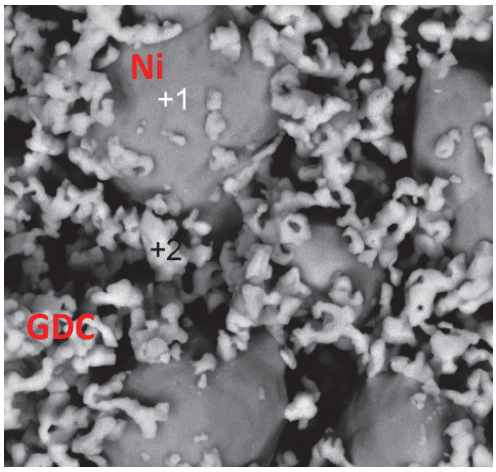

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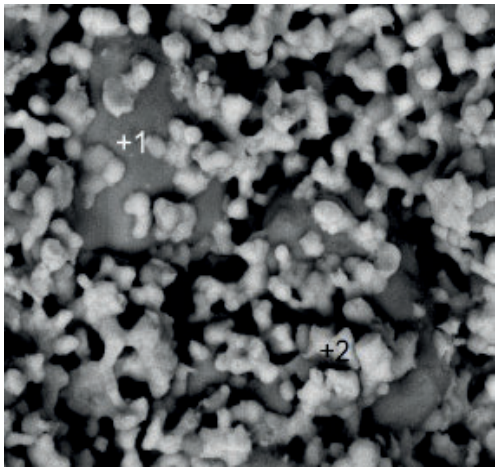

c)

Figure 6 a) EDX comparison with marked oxygen peak of b) reduced reference anode substrate with c) substrate after 500 h experiment

A reduced but unloaded cell was used as reference, with definitely no oxidized

nickel. When comparing Figure 6 b) with c), no significant differences in nickel grainsize or shape can be detected. Also considering the EDX spectra, no difference between the substrate composition can be assumed as the oxygen peak representing nickel oxide (marked and grey-colored) stays at the same size and shape. The different distribution of GDC on nickel grains cannot be argued as a result of the 500 h experiment but of manufacturing tolerances. Summing up, nickel re-oxidation after 500 h loaded operation in a gas mixture with 36 vol% H_2O could not be detected. However, slight changes in the distribution of substrate components might be possible but do not influence cell performance.

In conclusion, it can be claimed that fueling Ni/GDC anodes with a FBS gasifier product gas containing 36 vol% H_2O does not result in performance- or substrate degradation at a high electrical load.

4. Conclusion and Outlook

This work presents a comprehensive study on the influence of main gas components on the performance of an industrial-size SOFC relevant for the use with product gases from biomass gasification.

First, a literature review on the most promising cell configuration and biomass gasifier product gas compositions was done. ESC-SOFCs with Ni/GDC anode showed the highest potential for the use with biomass gasifiers due to (i) their higher tolerance against catalyst contaminants and thus better resistivity to solid carbon deposits than cells with Ni/YSC anode, as well as (ii) their lower risk of failure resulting from cracks in the anodic structure in comparison to ASC-SOFCs. Product gases from FBS gasifiers were rated as most promising for the use with SOFCs and are focused in this work.

Second, changes in cell characteristics when adding carbonaceous species CO, CH_4 and CO_2 while decreasing the N_2 content in a reference gas mixture of 50-25-25 vol% H_2-H_2O-N_2 representing a steam gasifier product gas were investigated: CO concentrations higher than 10 vol% result in an increase of the ASR and stagnating cell voltage and should be avoided. For the same reference mixture, CH_4 concentrations should not exceed 10-20 vol% to avoid CH_4/H_2O ratios smaller one and furthermore a strong increase of the ASR. The amount of CO_2 in the gas mixture should be aimed as low as possible, especially to avoid conversion of electrochemically high reactive H_2 with CO_2 to CO via WGS and to keep diffusion resistances low. Detailed electrochemical analyses of the presented results as well as experiments with higher fuel utilizations will help to further understand processes within the cell. The presented results from the parameter study confirm FBS product gas compositions as most suitable for the use with SOFCs.

Third, the 500 h degradation stability of a loaded cell fueled with steam-rich simulated FBS gasifier product gas was investigated showing no performance or substrate degradation, especially considering re-oxidation of anodic nickel. Experiments with higher fuel utilizations will increase degradation risks and therefore industrial relevance of presented results.

5. Acknowledges

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6. Abbreviations

ASC anode supported cell
ASR area specific resistance
EDX energy-dispersive X-ray spectroscope
EIS electrochemical impedance spectroscopy
ESC electrolyte supported cell
FBS fluidized bed steam
FDA fixed-bed downdraft air
LHV lower heating value
LSM lanthanum strontium manganite
MSR methane steam reforming
Ni/GDC nickel/gadolinium-doped ceria
Ni/YSZ nickel/yttria-stablizied zirconia
OCV open circuit voltage
SCR steam to carbon ratio
SEM scanning electron microscopy
SOFC solid oxide fuel cell
SSZ scandia stabilized zirconia
WGS water gas shift

7. List of symbols

U cell voltage [V]
i current density [mA/cm^2]
η_{el} electrical efficiency [%]
η_{conv} conversion efficiency [%]

8. Literature

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