Experimental Study for the Optimization of an Integrated BiomassGasifier-Fuel Cell System

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Abstract

The Solid Oxide Fuel Cells (SOFCs) is a promising solution to increase the share of renewables and raise energy efficiency. So, Optimal system integration and high durability of its components are both required. However, system optimization may ask for a compromise between optimal SOFC operating temperature and system thermal integration.

Typical producer gas compositions from downdraft fixed bed gasification with air (with and without drying) and fluidized bed gasification with steam are considered. So, the effect of temperature variation is analysed. The results show that, although a higher cell temperature (800°C) and a dry product gas composition lead to higher efficiencies, despite a decreased efficiency, this would optimize the gasifier-SOFC coupling. However, the presence of water in the producer gas (when drying is not included) reduces the possibility of carbon deposition. As a result, it increases the cell durability.

1. Introduction

Due to the climate change, there is a steadily growing demand for CO_2-neutral supply of heat and power. Combined heat and power (CHP) production by combustion of solid biomass, through steam cycles or organic Rankine processes (ORC), is an already consolidated technology. However, it offers low electrical efficiencies, even at large scales (in CHP operation, values around 20% can be obtained only for installations of tens of MW_{th}). On the other hand, biomass gasification offers higher efficiencies than combustion in all power ranges. The current state-of-the-art in CHP production through biomass gasification is represented by coupling a gasifier with gas engines, achieving an electrical efficiency close to 30% (up to 35% with the addition of an ORC) [1].

Higher electrical efficiencies can even be achieved when coupling biomass gasification with Solid Oxide Fuel Cells (SOFCs). SOFCs are preferred over other fuel cells due to the high operating temperature for heat utilization and high tolerance to typical producer gas components and impurities. A number of process simulations [2] and single cell tests [3] have confirmed the general suitability of the system with a real producer gas. Moreover, it is possible to achieve an electrical efficiency of over 40% [4], which is a significant increase in comparison to biomass gasification CHP systems with internal combustion engines [1]. Efficiency could be increased beyond 60% with the integration of an additional thermal cycle to exploit SOFC waste heat and unused fuel, i.e. a gas turbine or an ORC. Furthermore, producer gas utilization in a SOFC extremely reduces the emissions of NO_x and soot.

However, an adequate gas treatment is required upstream the SOFC in order to use the producer gas without hampering the fuel cell durability. Gas treatment may include: i) conditioning, to adjust the water content and ii) cleaning, to remove impurities such as sulphur, dust or (in some cases) tars [5]. This is necessary to extend SOFC lifetime, smoothing the possible causes of fast degradation. In order to optimize the "real-world" system applied, increasing its overall efficiency and enhancing SOFC operation, this study focuses on experimental and numerical investigations and discussion of appropriate operating conditions for the purpose mentioned.

1.1. Biomass gasification

Several gasification technologies are commercially available. Beyond the biomass feedstock, the oxidizing medium (air or steam) and the gasification technology strongly determine the producer gas quality regarding calorific value and impurities load. The more relevant technologies for CHP applications are fixed-bed downdraft gasification (DDG) and fluidized bed gasification (FBG), for small and medium power ranges respectively. In DDG the inner temperature distribution leads to a very low tar content [6], which is inside the tolerance levels of commercial SOFC anodes, as several researchers have already demonstrated [3,7,8]. Moreover, the simplicity of construction makes this technology feasible for small scales, especially when atmospheric air is supplied as oxidizer. However, gasification with air leads to a producer gas with a low calorific value, as inert species concentration may exceed 60%vol (nitrogen and carbon dioxide). At bigger scales, FBG gasification with steam is more promising, leading to a producer gas with a higher calorific value, although with a major tar content

1.2. Integration of biomass gasifier and fuel cell systems

Thermal aspects are fundamental to improve the overall energy efficiency at system level. The temperature of a biomass gasifier is commonly in the range of 700-800°C and current state-of-the-art SOFCs are usually run at temperatures of 750-800°C. Whilst the affinity in temperature ranges facilitates the coupling, the direct feeding of hot producer gas to the SOFC is not possible because an intermediate gas cleaning section is called for reducing the impurities load. Even for hot gas cleaning methods [5], the producer gas undergoes a temperature drop of a few hundred degrees before impurities removal.

Nomenclature

AC	Alternate Current	EIS	Electrochemical Impedance Spectroscopy
CHP	Combined Heat and Power	FBG	Fluidized Bed Gasifier
DDG	Downdraft Fixed Bed Gasifier	ORC	Organic Rankine Cycle
DOE	Design of Experiment	SOFC	Solid Oxide Fuel Cell

Therefore, to cope with heat recovery limitations while avoiding the combustion of a major fraction of the producer gas in an auxiliary afterburner, it is useful to reduce the SOFC operating temperature in order to deal with the upper temperature level superimposed by the gasification step.

The objective of this work is to investigate how system integration requirements affect the performance of the SOFC and to give an overview for different system configurations. Typical producer gas compositions from an air-DDG (with and without gas conditioning) and steam-FBG (with gas conditioning) will be considered for application in SOFC cells based on (i) numerical thermodynamic equilibrium calculations and (ii) experimental investigations of the cell performance at two temperatures: 750 and 800°C. Compared to the current state-of-the-art, this research aims at evaluating SOFC operability in working conditions which are proposed for system integration optimization. Nonetheless, temperature is not only regulating thermal integration at system level, but also acting as the main driver for cell materials degradation, especially when carbon-containing gas mixtures are employed as fuels for the SOFC. Hence, providing a deep performance screening is necessary to assess system integration before planning further durability test campaigns.

2. Experimental Setup

2.1 Materials and test rig

For the purpose of this study, commercial anode-supported NiYSZ/YSZ/LSCF SOFCs of industrial size (chemical active surface: 9x9 cm^2) are employed. On the anode side, a nickel mesh is used to contact the cell, while a platinum one is applied on the cathode side. The cell is embedded in a ceramic housing. The operating temperature distribution during the cell operation is measured in 16 different spots within the cell housing.

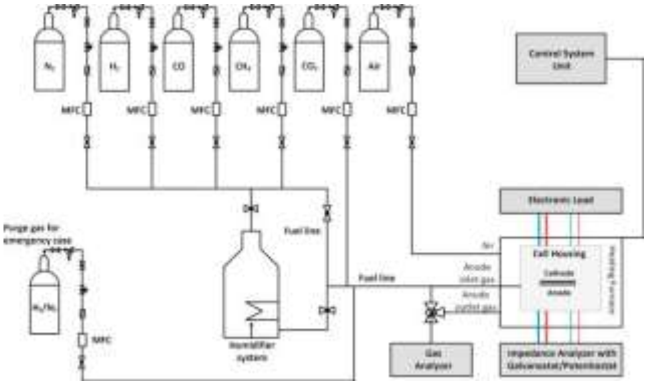

Fig. 1. Test rig [9].

A complete sketch of the test rig is reported at Fig. 1. As it can be seen from the figure, the cell anode is fed with a simulated producer gas, obtained by mixing pure gas components (N_2, H_2, CO, CO_2 and CH_4), in agreement to proportions of technical interest. The cell anode feeding is enriched with steam in a humidifier system, based on the water bubbler humidification principle, whereby CO_2 is admixed with the other gases just after it, because of CO_2 solubility into water. On the cathode side, the SOFC is supplied with compressed air. An ABB gas analyser is used to determine the volumetric gas composition both at the anode inlet and outlet. To the aim of electrochemical investigations, the rig is equipped with a Bio-Logic impedance analyser with an 80-A booster. The galvanostatic techniques is applied, superimposing an AC current wave featuring frequencies in the range 100 mHz-10 kHz. For each test, voltage measurement, polarization, electrochemical impedance spectroscopy (EIS) and off-gases analysis are conducted. The EIS measurements are performed both at OCV and under load.

2.2 Methods and DOE

In order to analyse the impact of the biomass gasification producer gas on the SOFC performance, various gas mixtures are used, as shown in Table 1. Air-DDG and Steam-FBG are considered as the most relevant gasification cases to be investigated (see Section 1). Regarding gas conditioning, two options are considered for Air-DDG producer gas: i) complete drying, ii) no conditioning. Both options are feasible, since the water content in the unconditioned gas is low. On the other hand, steam-FBG producer gas is tested only considering drying as preliminary conditioning. As a matter of fact, steam gasification leads to a very high water fraction at the reactor outlet, which is considered as a drawback for at least two reasons: first, water decreases the gas calorific value and second, it leads to a faster ageing of the SOFC performance. Finally, considering a maximum temperature swing of 50°C due to coupling constraints, the SOFC is tested under the same anode feeding mixture at 800°C, representing the upper bound, and 750°C, representing the lower bound. All of the tests with simulated gas mixtures are made under the assumption that cleaning of impurities has been performed to cope with SOFC materials tolerance level. Hence, in this experimental characterization, impurities such as sulphur compounds, dust and tars are neglected.

Table 1: Design of experiment matrix with composition details for biomass producer gases used as a fuel for SOFC.

Gasification	Gas	SOFC	Gas bulk composition (volume basis)

	technology	conditioning	temperature	CH_4	CO	CO_2	H_2	H_2O	N_2
Test A-1	Air DDG	Drying	800°C	5%	20%	15%	20%	0%	41%
Test B-1	Air DDG	None	800°C	4%	17%	12%	17%	15%	35%
Test C-1	Steam FBG	Drying	800°C	11%	24%	21%	37%	0%	8%
Test A-2	Air DDG	Drying	750°C	5%	20%	15%	20%	0%	41%
Test B-2	Air DDG	None	750°C	4%	17%	12%	17%	15%	35%
Test C-2	Steam FBG	Drying	750°C	11%	24%	21%	37%	0%	8%

3. Results and Discussion

3.1. Thermodynamic equilibrium and prediction of carbon depositions on SOFCs

The ratio of hydrogen and oxygen to carbon are crucial factors that both impact the formation of carbon and generally define the operation conditions of SOFCs employed. Therefore, the presentation of these three components in one diagram - a ternary C-H-O diagram – is of great importance. Fig. 2 shows the C-H-O ternary diagram representing the carbon deposition region, as well as the region where carbon-free operation is ensured. They are delimited by a carbon deposition boundary line, which is a function of temperature. When operating the SOFC with simulated producer gas mixtures as in Table 1, the operating points under SOFC conditions are calculated at the equilibrium state and shown in the C-H-O diagram, thus predicting if carbon deposition is being provoked or suppressed.

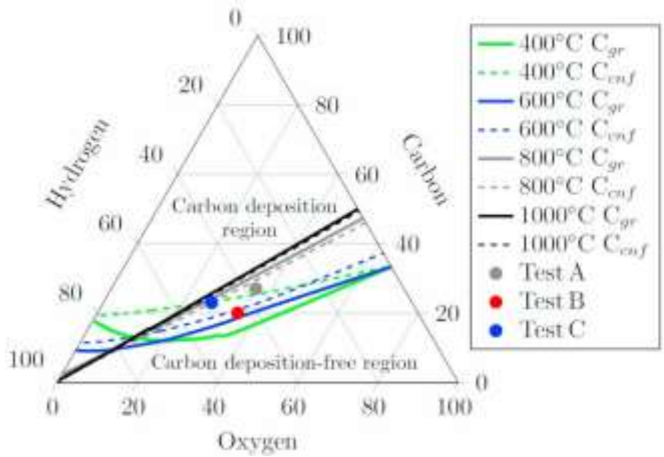

Fig. 2. C-H-O ternary diagram for SOFC operation under gas mixtures given in Table 2.

The likelihood for carbon to be formed decreases with the increasing temperature for all cases. When using humidified fuel (red point – TEST B), it is more likely that carbon will not be formed at SOFC operating temperatures of 750 - 800°C. However, when using dry gas mixtures (grey and blue points – TESTS A and C), the SOFC operating points are positioned exactly on the boundary between the carbon-free and carbon-deposition region, thus shifting the cell towards the critical operating range.

3.2. Experimental examination of SOFCs

Three different biomass producer gas mixtures mentioned above are used as a fuel for SOFCs. The overall cell performances are shown in Fig. 3 by means of polarization curves. When operating SOFC at 750°C, the best performance is achieved by using Steam-FBG dry gas mixture (Test C-2). This was expected since that gas composition shows the lowest amount of inert species (carbon dioxide and nitrogen) which makes concentration losses milder. No significant deviation in the maximum power is seen between mixtures TEST A-2 and B-2, where the fuel components are present in similar amounts. The maximum current density achieved is 500 mA/cm² at 0.7V.

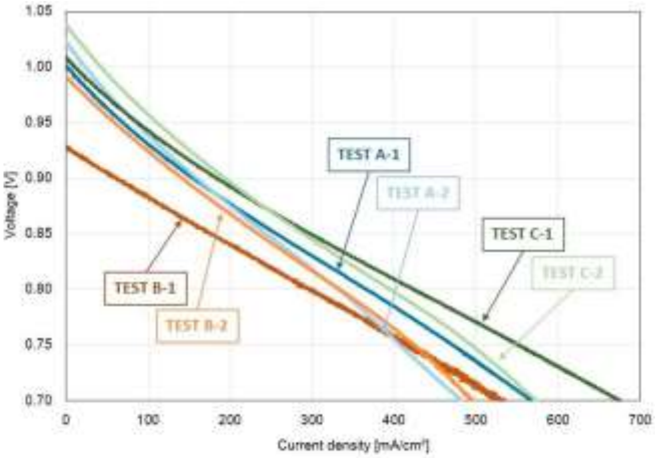

Fig. 3. Polarization curve measured during SOFC operation with biomass conversion products at temperatures 750°C and 800°C.

Increasing the operating temperature up to 800°C significantly improved the performance of the SOFC for all of the producer gas mixtures used, and the maximum current density at 0.7 V is increased by almost 20% compared to tests at 750 °C. Increasing temperature resulted also in decreasing losses, which are carefully investigated by means of electrochemical impedance spectroscopy. Fig. 4 shows EIS spectra obtained during the operation at the temperature of 750°C, in order to identify the polarization losses that occur under most efficient system integration conditions. When operating the cell at low current (50 mA/cm²), TEST B-2 resulted in the lowest losses, since the anode feeding used is a humidified fuel. Conversely, the two other mixtures (TEST A-2 and C-2) do not contain water vapour, and the activation losses are higher, since an activation energy is required to produce water. This is especially visible at frequencies lower than 10 Hz. Although losses for TEST B-2 are very moderate at low current density, they significantly increase with the rising load. Hence, when operating the SOFC at 500 mA/cm², TEST B-2 scores the highest impedance, since the high water vapour concentration causes diffusion losses. Under TEST C-2 operating conditions, diffusion losses are the lowest, because of the higher availability of fuel active species even at increased current load.

Based on the introduction and the evidence provided by the results, case B-2 has been selected as the most interesting condition considering system integration, cell durability and performance stability. Downdraft reactors are better candidates for a matter of scale and higher gas quality (less tars). To run the cell at a lower temperature (i.e. 750°C) facilitates the thermal integration of the system, avoiding the combustion of a major slipstream of the producer gas to cope with heat shortage. Moreover, since a deep gas conditioning to completely remove water from the biomass producer gas would increase the system complexity and reduce efficiency, an un-conditioned gas is preferred. Besides, the presented results show that for this case (B-2) a reasonable efficiency can be achieved and it will be selected for future investigations regarding cell degradation during long-term operation.

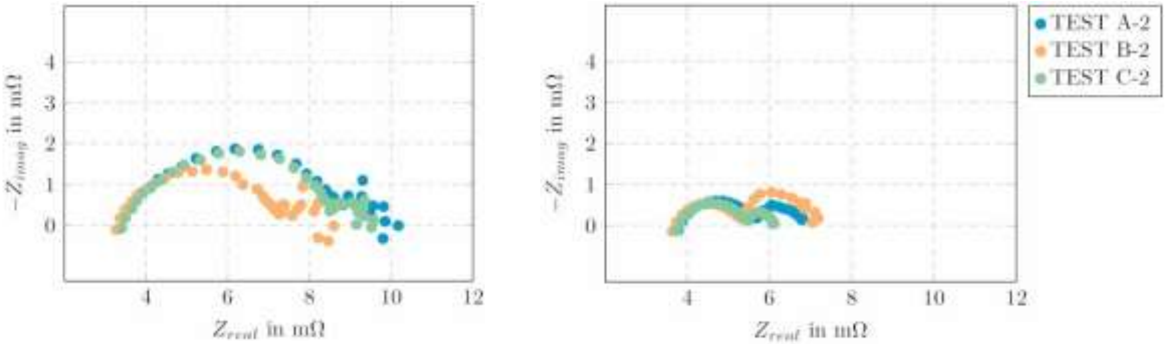

Fig. 4. Electrochemical impedance spectra obtained for 3 different produced gas mixtures at 50 mA/cm² (left) and 500 mA/cm² (right).

4. Conclusions

The present paper provided experimental results in support of the highly efficient and environmentally friendly coupling of SOFCs and biomass gasifiers. With regard to the biomass gasification stage, two different gasifier types and gas conditioning were considered. The tested SOFC was operated under different simulated producer gases at 750 and 800°C. For a matter a system complexity reduction and optimized thermal integration, the case of un-conditioned downdraft gasifier producer gas and SOFC operated at 750°C was selected as the most interesting. In addition to the system integration advantages, this case seems to be an adequate choice for cell durability and performance stability, despite an acceptable – but still reasonable - reduced efficiency. The results observed represent a first step in system development and optimization. As temperature does not only influence thermal integration but also is the major driver regulating the likelihood of passive degradation, future experiments will be focused on cell degradation for this case to investigate if this pathway is a viable solution for long-term operation.

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