

# THERMO-ECONOMIC AND EXPERIMENTAL INVESTIGATION OF SMALL TO MEDIUM-SCALE INTEGRATED BIOMASS GASIFICATION SOLID OXIDE FUEL CELL SYSTEMS

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**ABSTRACT:** In this study the combination of Solid Oxide Fuel Cells and allothermal biomass gasification systems is investigated. Several problem fields are addressed, such as gas cleaning, exhaust heat utilization and overall heat integration, thus aiming for higher system efficiency, increased flexibility and lower cost. Furthermore experimental activities are described, which consider the effect of tarry substances from the gasifier on solid oxide fuel cells.

**Keywords:** biomass, solid oxide fuel cell, gasification, simulation, experiment, tar

## 1 INTRODUCTION

High temperature fuel cells, such as the solid oxide fuel cells (SOFC), are the most efficient device for conversion of fuel to electricity. Biomass is one of few renewable energy sources which can, in contrast to wind and solar energy, be used in reliable fashion. Thus, combining biomass with SOFC by means of gasification is promising a highly efficient, reliable way of electricity production without CO<sub>2</sub> emissions. If combined with carbon capture and storage (CCS), even a negative CO<sub>2</sub> balance seems possible.

However, despite biomass gasification slowly becoming state-of-the-art, in current systems the achieved gas quality is far too low for application in fuel cells. Furthermore system costs are currently not ready for competing with conventional systems.

Thus, in the frame of the FCH-JU project SOFCOM, necessary contaminant limitations for integrated biomass gasification-SOFC systems are studied experimentally by means of single cell testing with contaminant loaded synthesis gases. The main focus of the research is the effect of tar compounds on SOFC anodes, in particular the interaction of different tar classes present in the bio-syngas at the SOFC anode. Here, competition of the different tars beneath each other and the other syngas components for the available catalyst sites can lead to increased or decreased carbon deposition and thus varying degradation rates of the anode structures. For this purpose, different concentrations of the chosen model tars Toluene, Phenol, Naphthalene, Biphenyl, Fluorene and Flouranthene are added to a synthetic gasification product gas mixture.

In addition to the experimental investigations novel system concepts are studied in thermo-economic simulations with the aim to achieve higher system efficiency, increased flexibility, heat recovery and lower costs. Especially it is shown that utilization of SOFC waste heat in indirectly heated fluidized bed gasifiers can increase the overall system efficiency based on LHV biomass input by up to 15% by avoiding the necessity to produce heat through combustion of a part of the biomass, while decreasing system costs with optimized component integration.

## 2 EXPERIMENTAL INVESTIGATION OF EFFECTS OF TAR ON SOFC ANODES

Experimental investigations of the impact of tar

compounds on SOFC anodes are carried out using a fully automated tar mixing station connected to a FUELCON Evaluator C1000-HT test station via a trace-heated pipe. Within the test station an artificial product gas is provided to single SOFC cells. The composition of the product gas composition can be varied in a wide range using mass flow controllers. The utilized dry gas composition is 50%<sub>vol</sub> H<sub>2</sub>, 20%<sub>vol</sub> CO, 20%<sub>vol</sub> CO<sub>2</sub>, 10%<sub>vol</sub> CH<sub>4</sub>, which is similar to typical operating conditions of an indirectly heated bubbling fluidized bed steam gasifier [2]. Steam is added in a bubbler at saturated conditions, thus the overall steam content is controlled via the bubbler temperature. For investigating the temperature distribution profile along the cell 9 thermocouples are implemented in the ceramic cell housing in an equally spaced square pattern. The operating conditions are chosen similar to typical conditions in an SOFC stack. The cell is operated at atmospheric pressure, the operating temperature is 750°C, measured at the middle of the cell. The fuel utilization factor is chosen to be 60%.

The tar mixing station consists of 6 identical containers, each one containing one specific tar compound. A separate carrier gas stream is utilized for each container, which is saturated with the desired tar compound. In order to control the amount of tar in the carrier gas, the containers are heated to control the partial pressure of the tar substances. Currently CO<sub>2</sub> is used as the carrier gas, since it is already a component of the chosen artificial product gas composition, which prevents dilution in contrast to e.g. using N<sub>2</sub>, and furthermore has to bypass the bubbler anyway, since it is soluble in water. The carrier gas stream is pre-heated to the container temperature before entering and trace-heated when saturated with tar until it is fed into the SOFC anode in order to prevent tar condensation. The chosen model tar components and concentrations are shown in Table I.

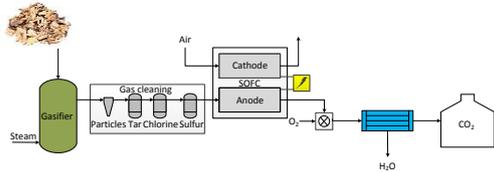
**Table I:** Model tar compounds, classification after [1], in g/Nm<sup>3</sup>

Class	Compound	Concentration in product gas [2]	Max.concentration in experiment
2	Phenol	< 1.19	5
3	Toluene	< 1.50	5
4	Naphthalene	< 1.79	5
5	Flouranthene	< 0.11	0.25

### 3 THERMO-ECONOMIC SYSTEM ANALYSIS

#### 3.1 Overall system concept

In the general system concept studied in the presented work, which is shown in Figure I, a biogenous feedstock, e.g. woody biomass, is fed into a gasifier, together with a gasification agent, i.e. steam.



**Figure 1:** Overall system concept

Utilizing high temperature heat, the biomass is gasified forming a product gas mixture mainly composed of  $H_2$ ,  $CO$ ,  $CO_2$ ,  $H_2O$  and  $CH_4$  with additional trace substances, such as  $H_2S$ . Since the trace substances are harmful for downstream equipment, they subsequently have to be cleaned from the product gas. After the cleaning section, the product gas is re-heated if necessary and fed into the anode of an SOFC unit. Here, a major part of the chemical energy of the fuel is converted into electricity and heat. After the SOFC leftover fuel is post-combusted and the resulting heat is further utilized for different purposes. If the post combustion is done almost stoichiometrically with sufficiently pure oxygen, the resulting gas stream consists of a mostly pure mixture of only  $H_2O$  and  $CO_2$ . From this mixture the  $H_2O$  can be separated by condensation and, if necessary, further purification steps e.g. utilizing membranes in order to achieve a stream of sufficiently pure  $CO_2$  for transport, storage or other applications.

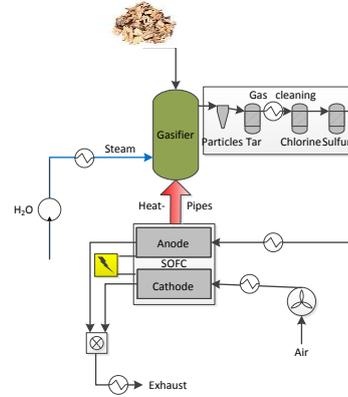
#### 3.2 Heat integration between SOFC and gasifier

The main focus of the presented study is heat integration between the SOFC and the gasifier. For indirectly heated gasification typically between 25 and 35% of the feedstock heating value has to be introduced as heat. For this purpose different technologies have been proposed. One very promising concept is the heat-pipe reformer. It allows introduction of heat into the gasification chamber almost isothermally via the heat-pipes. If the hot ends of the heat-pipes are connected to either the post combustion chamber of the SOFC exhaust, or included in the SOFC stack itself, heat generated in the SOFC can be directly supplied to the gasification chamber, as shown in Figure II. Thus the heat is effectively recycled, at least reducing the necessity for combustion of a part of the feedstock in order to supply the heat for the gasification process.

#### 3.3 System optimization

The performances of the gasification process itself, as well as that of the SOFC, are regarded as given parameters for this study. The same applies for all other major equipment. Overall the aim is to utilize already existing components in order to achieve a realistic system design. For optimization of the system concept only the arrangement of the existing components can be adjusted in order to reach optimal heat integration. Heat integration is performed according to the pinch-point approach. The simulation models for the presented studies are built in Aspen Plus®, the optimization and

heat integration are carried out using OSMOSE, a Matlab®-based optimization tool developed by the École Polytechnique Fédérale de Lausanne (EPFL).



**Figure II:** Heat integration via heat-pipes

#### 3.4 Results

The gasifier is assumed to work with wood chips with the composition shown in Table II. The moisture content is set to a typical value of 15%.

**Table II:** Biomass input (wood chips) [3]

Biomass input	Unit	Value
Ash	% dry	0.55
C	% dry	49.8
H	% dry	6.3
N	% dry	0.13
O	% dry	43.2
LHV dry	MJ/kg	18.8

Operating conditions of the gasifier and the resulting product gas composition are given in Table II. The product gas composition is typical for a fluidized bed gasifier [2]. As a result of the endothermic gasification reactions for a 500kW feedstock energy input 167kW of heat have to be supplied to the gasifier in order to sustain the thermal balance of the gasification. These are supplied by combustion of residual charcoal and post combustion of residual anodic fuel in a combustion chamber, as well as excess heat from the SOFC, both connected to the gasifier via heat-pipes.

**Table III:** Gasifier operating conditions and performance

Gasification conditions	Unit	Value
Heat energy input	kW	167
Feedstock energy input	kW	500
Pressure	bar	1.5
Temperature	°C	800
Estimated heat loss	kW	7
Mass flow rate	kg/h	188.8
$H_2O$	%	36.2
$CO$	vol-%(dry)	22.9
$CO_2$	vol-%(dry)	20.9
$H_2$	vol-%(dry)	42.6
$CH_4$	vol-%(dry)	10.6
$N_2$	vol-%(dry)	2.9
LHV	MJ/kg	9.2
Chemical energy content	kW	481.0

The resulting chemical energy content of the fuel is thus very high, compared to conventional systems. For modelling the SOFC a very conservative approach was selected using data of a tubular Siemens fuel cell, which is easily outperformed e.g. by more modern anode supported cells. The relevant parameters are given in Table III. Especially the temperature spread between inlet (1008K) and outlet (1038K) of the cells is limited to a conservative value of 30K. Pressure losses are set to 0.2 bar and also for the inverter efficiency a low value of 92% is assumed.

**Table III:** SOFC operating conditions and performance [4], [5], [6]

SOFC parameters	Unit	Value
Operating temperature	°C	850
$\Delta T$ (in/out)	°C	30
Pressure losses	bar	0.2
Inverter efficiency	%	92
Cell voltage	V	0.72
Total active area	m <sup>2</sup>	150
DC power	kW	216.1
AC power	kW	198.8
Auxiliary consumption	kW	18.6
Net AC output	kW	180.2
DC efficiency of SOFC	%	46
AC efficiency of SOFC	%	42
Net efficiency of the plant	%	36

This overall leads to a fairly low net efficiency of the plant of 36%. Nevertheless it is shown that the chemical energy content of the product gas is significantly increased compared to conventional operation of a heat-pipe reformer, where normally already around 33% of the biomass input are fed directly to the combustion chamber in order to produce the necessary heat for the gasification. Furthermore, in the presented system around 114.5kW of heat are available, which in the present model are for simplicity removed by cooling water. This heat can be applied e.g. for district heating purposes, thus increasing the overall efficiency of the plant to 58.9%.

#### 4 CONCLUSION

In this paper a new approach has been investigated for decentralized utilization of biomass residues based on the combination of fluidized bed gasification and solid oxide fuel cells. A plant with efficient heat integration between gasifier, post combustion and SOFC via heat-pipes was simulated in Aspen Plus<sup>®</sup>.

In the present model an electrical efficiency of 36% and an overall efficiency of 58.9% are achieved, based on a fairly small scale biomass thermal input of 500kW. It is shown that especially by utilizing excess high temperature heat via heat-pipes for the gasification the usual combustion of feedstock biomass can be avoided, resulting in a higher chemical energy content of the produced gas, which is then available for the SOFC.

Following studies will focus on the optimization of the heat integration and application of newer SOFC technology in order to increase the electrical output of the integrated plant configuration.

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