

## **Reference System for a Power Plant Based on Biomass Gasification and SOFC**

**Richard Toonssen, Nico Woudstra, Adrian H.M. Verkooijen**

Delft University of Technology  
Energy Technology, Process & Energy department  
Leeghwaterstraat 44  
2628 CA Delft / The Netherlands  
Tel: +31 (0)15 278 2153  
r.toonssen@tudelft.nl

### **Abstract**

The fossil fuel reserves are declining leading to a search for more efficient ways to produce electricity from these fossil fuels. One of the promising options is the solid oxide fuel cell gas turbine (SOFC-GT) hybrid system. A recent study has shown that it is possible to achieve exergy efficiencies of around 80% with a natural gas fueled SOFC-GT hybrid system. Although there are still many problems to solve before such systems can be built, this technique appears to be promising. The SOFC-GT hybrid system is also considered for application with biomass as the primary fuel. As the SOFC-GT requires a gaseous fuel, the biomass has to be gasified first. The generated bio-syngas contains mainly hydrogen, carbon monoxide, methane, water and carbon dioxide. Biomass gasification is considered to be carbon dioxide neutral, due to the short CO<sub>2</sub> cycle of biomass. In that case the combined biomass gasification SOFC-GT system appears to be an attractive option for the application of renewable sources of primary energy.

Combining biomass gasification and a SOFC-GT system introduces additional uncertainties, because the gas produced by biomass gasification will contain a variety of impurities like particulates, tars, alkali metals, halogens and sulfur compounds. These impurities will have an adverse effect on the efficiency and the lifespan of the SOFC-GT hybrid system. Appropriate gas cleaning will be necessary to remove these impurities almost completely. Gas cleaning is possible at different temperature levels. In general low temperature gas cleaning and high temperature gas cleaning are distinguished. Low temperature gas cleaning is more close to maturity than the high temperature one. However in the field of gas cleaning there are still many uncertainties, especially with regard to high temperature gas cleaning. An important uncertainty is that insufficient information is available about the tolerance of the fuel cell for the various impurities. In spite of all these uncertainties, the combination of a SOFC-GT hybrid system with biomass gasification is expected to be a challenging option for future energy conversion.

In this paper a system design will be presented, that combines biomass gasification with a SOFC-GT hybrid system. The purpose of this system is to serve as a reference for future design evaluations of full scale power systems. The reference design consists of a gasification unit, a gas cleaning system, a SOFC-GT hybrid system and a heat recovery system. The Fast Internal Circulating Fluidized Bed (FICFB) gasification system is selected for the conversion of biomass (wood) into bio syn-gas since the development of this technology has made significant progress. The generated bio-syngas will be cleaned in a low temperature gas cleaning system. The cleaned gas will be converted in the SOFC-GT hybrid system; residual heat will be used in a steam bottoming cycle.

An exergy analysis is made to evaluate the thermodynamic performance of the designed system. The results of this analysis are used to improve the system performance. The system is designed for a gross electrical output of 30MW.

## Introduction

Due to growing concerns about global warming and climate changes, the search for more sustainable ways of electricity production is increasing. This does not only involve the search for more sustainable sources of energy, but also the search for more efficient ways to convert available fuels into the demanded energy. One of the most promising fuels for electricity production is biomass, due to its short carbon cycle. Therefore biomass is considered to be CO<sub>2</sub> neutral. Since most biomass sources are in a solid state, it is difficult to convert biomass directly into electricity. Therefore, the biomass has to be converted first into a more convenient energy carrier. One option is the gasification of biomass, which converts biomass into bio-syngas. This bio-syngas can be applied in a variety of energy conversion processes.

One energy conversion process, which seems very attractive, is the solid oxide fuel cell gas turbine (SOFC-GT) hybrid system. Earlier system studies have shown that exergy efficiencies over 80% are possible with natural gas fuelled SOFC-GT hybrid systems [1]. By combining biomass gasification with a SOFC-GT hybrid system can lead to an efficient power production plant.

This paper presents a system design for a power plant based on biomass gasification and a SOFC-GT hybrid system. The plant is fueled with A-quality wood and the gross electricity production is around 30 MW<sub>e</sub>. This system design is based on existing technology as far as possible, so it can serve as a reference system for future design studies. By performing an exergy analysis, a clear picture is obtained of the losses and the true thermodynamic efficiency can be determined.

## System configuration

The system consists of four subsystems; the gasifier, gas cleaning, SOFC-GT hybrid system, and the heat recovery. These components are connected in the order as shown in figure 1.

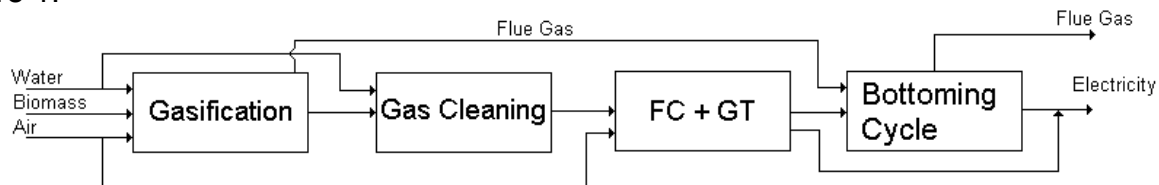


Figure 1 block scheme of the system design

In the following sections each of the subsystems will be discussed separately, starting with the gasifier.

### The gasifier

For the gasification process the Fast Internal Circulating Fluidized Bed (FICFB) is used. This gasifier is developed by the Institute of Chemical Engineering and AE Energietechnik [2-4]. It is an indirect gasifier, which produces a medium caloric value gas ( $\pm 12$ -14 MJ/kg). The gasification process contains a combustor, which operates at 1000°C and a pressure of 1.5 bar, and a gasifier operating at 800-900°C and a pressure of 1.5 bar. Heat is transferred from the combustor to the gasifier by circulating the bed material between the gasifier and the combustor. Such a gasifier of 8 MW<sub>th</sub> input has been operated for many years in Güssing Austria [2].

### The gas cleaning

The gas coming from the gasification unit cannot directly be used in a SOFC-GT hybrid system, because it contains several impurities, which are harmful to the fuel cell and or gas turbine. Therefore gas cleaning is necessary. The impurities in the bio-syngas and the assumed tolerances of the fuel cell are listed in table 1.

**Table 1, impurities in the producer gas and the assumed tolerance of the SOFC-GT**

<b>Impurity</b>	<b>Amount in gas</b>	<b>Tolerance of the SOFC-GT</b>
Particulates	10-20 g/Nm <sup>3</sup> [2]	< 1ppm (10-20 µm) [5]
Tars	0.5-15 g/Nm <sup>3</sup> [2]	< 1ppm
Alkalis	No Data Available	< 0.1ppm [5]
Sulfur	20-50 ppm [2]	< 1ppm[5-7]
Chlorine	No Data Available	< 1ppm[6, 7]

Gas cleaning will be performed at low temperature, since high temperature gas cleaning is not yet proven [8]. The gas needs to be cooled prior to the cleaning. The gas is cooled in a heat exchanger; the discharged heat can be used in a bottoming cycle. During the cooling a large part of the alkali metals will possibly condense onto the particles entrained in the gas [5]. Also some of the tars will condense. The temperature is chosen well below the dew point of the alkalis, around 120°C. The particles and the condensed alkalis are removed by filtering the cooled gas. Then the gas is scrubbed with water in order to remove the halogens, tars and residual alkalis from the gas. During the scrubbing the gas cools down further, the temperature of the gas leaving the scrubber is approximately 65°C. After scrubbing the gas is compressed to 8 bar, in order to meet the requirements for the SOFC-GT. The compressed gas is led through a packed bed with ZnO. This is supposed to be necessary to remove any sulfur compounds from the gas. To make sure that also the last particles in the gas will be removed, the gas is finally passed through a ceramic filter.

### **The SOFC-GT hybrid system**

The SOFC-GT hybrid system consists of solid oxide fuel cell (SOFC), which partly replaces the combustor of the gas turbine (GT). The cleaned gas is fed to the anode, and compressed air is fed to the cathode. In the fuel cell the clean gaseous fuel is converted directly into electricity. Part of the anode off-gas is recycled to the anode feed; also part of the cathode off-gas is recycled to the cathode feed to preheat the fresh air supplied to the stack. The anode recycle is used to increase the steam to carbon ratio in the cell, since a high steam to carbon ratio prevents carbon deposition [9].

The fuel cell is a direct internal reforming SOFC, which enables the conversion of the methane in the syngas into hydrogen and carbon monoxide. The off-gasses are passed to a combustor, where the residual combustible components are burnt using the cathode off-gas flow. The flue gasses are expanded in a turbine for additional power generation. The expanded flue gas is used to recuperate the incoming air after compression. The turbine is connected to a compressor, which is used to compress the air needed for SOFC-GT hybrid system, and a generator. In this way extra electricity is produced.

### **Heat Recovery**

Since the SOFC-GT hybrid system generates more heat than necessary for the various heating purposes, a considerable amount of excess heat is available for application in a bottoming cycle. Heat can be transferred from the system during the cooling of the producer gas before gas cleaning and from the hot flue gas coming from both the gasifier and the SOFC-GT hybrid system. For these sources two separate boilers are added, which generate high pressure steam for a bottoming cycle. All the steam is expanded in a single turbine, which is coupled to a generator, for additional electricity production.

### **System Modeling**

For the described system a steady state model is created using the program Cycle Tempo [10], an in house developed flow sheeting program for the evaluation of energy conversion systems. Actually two models are developed one for the biomass gasification with gas



input values of the heat transfer fluids in this system model are adopted from the results of the system model of figure 2. The hot gas flows are cooled in two different boilers consisting each of a economizer, an evaporator and a superheater. The steam generated by these boilers is expanded in a single turbine. Several assumptions have been regarding the heat recovery system.

- The turbine has an isentropic efficiency of 84.96% and a mechanical efficiency of 99%.
- The pumps have an isentropic efficiency of 75% and a mechanical efficiency of 99%.
- The pressure of the deaerator is set to 1 bar.
- The condenser pressure is set to 0.03 bar (assuming a water cooled condenser).
- The pressure of the superheated steam at steam turbine inlet is 38.58 bar and the temperature is 530°C.

A flow scheme of the steam bottoming cycle is given in figure 3.

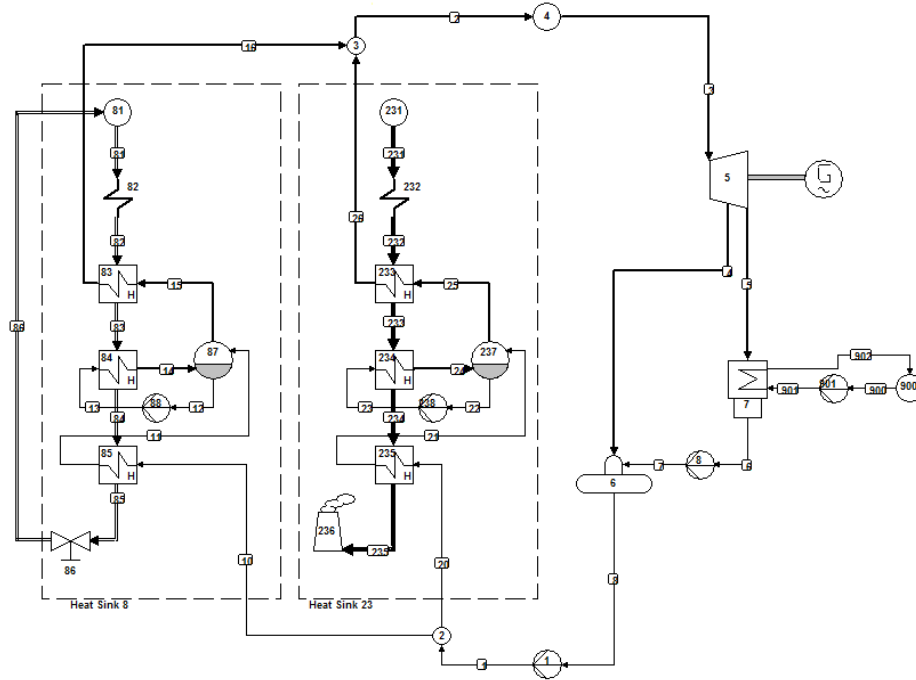


Figure 3 flow diagram of the steam bottoming cycle

The dry composition of the biomass used in the system calculations is given in table 2. The assumed moisture content of the biomass is set to 25.2 wt%.

Table 2 dry composition of the used biomass in the model

	Amount	Unit
Carbon (C)	49.97	wt%
Hydrogen (H)	6.12	wt%
Nitrogen (N)	0.55	wt%
Oxygen (O)	42.49	wt%
Sulfur (S)	0.06	wt%
Ash (SiO <sub>2</sub> )	0.80	wt%
Lower Heating Value (dry)	18620	kJ/kg
Exergy (dry)	20611	kJ/kg

The environmental conditions, as used for the calculation of exergy values, are set to a pressure of 1.01325 bar and a temperature of 15°C, the composition of the environment is defined as presented in table 3.

**Table 3 chemical composition of the environment**

<b>Component</b>	<b>Mole fraction [%]</b>	<b>Component</b>	<b>Mole fraction [%]</b>
Al <sub>2</sub> O <sub>3(s)</sub>	0.01	O <sub>2</sub>	20.60
Ar	0.91	SiO <sub>2(s)</sub>	0.01
CO <sub>2</sub>	0.03	SO <sub>2</sub>	0.01
H <sub>2</sub> O	1.68	Cl <sub>2</sub>	0.01
N <sub>2</sub>	76.73	F <sub>2</sub>	0.01

## Results

It is assumed that a biomass fuel flow of 4.12 kg/s is fed to the gasifier at a pressure of 1.5 bar and a temperature of 15°C. This resulted in a gross power of the gasification SOFC-GT hybrid system (without bottoming cycle) of 28.78 MW<sub>e</sub>. Water and air are fed to the system at environmental conditions; the amounts are calculated by the model. The amount of water needed for the gasification process is 1.302 kg/s, and the air flow to the gasifier is 7.952 kg/s. This results in a producer gas with the dry composition as shown in table 4, at a temperature of 817°C and a pressure of 1.48 bar.

**Table 4 main dry composition of the producer compared with the literature [2]**

<b>Component</b>	<b>Output model [mole%]</b>	<b>Literature data [vol%]</b>
Hydrogen (H <sub>2</sub> )	35.22	30-40
Carbon monoxide (CO)	22.63	20-30
Carbon dioxide (CO <sub>2</sub> )	20.86	15-25
Methane (CH <sub>4</sub> )	17.18	8-12
Nitrogen (N <sub>2</sub> )	3.93	1-5

In addition to the produces gas, the gasifier produces also 0.026 kg/s ash and 9.087 kg/s flue gas. The temperature of the flue gas from the combustor is 1364°C. This hot flue gas is used for pre-heating the air to the combustor and to produce steam for the gasification process. The temperature of the flue gas after air pre-heating and steam production is 789°C. Then the flue gas is used to preheat the producer gas coming from the gas cleaning section. The flue gas leaves the producer gas preheater at a temperature of 689°C. Then the flue gas is mixed with the flue gas from the gas turbine outlet; the mixed gas has a temperature of 617°C. The flue gas mixture is cooled further in the heat recovery boiler to generated steam for the bottoming cycle. The flue gas is transferred to the stack at a temperature of 162°C.

After gasification the producer gas enters the gas cleaning subsystem where it is cooled to 110°C and cleaned in a bag filter before scrubbing. During cooling 6032.28 kW of heat is extracted. The producer gas is scrubbed with 8.95 kg/s water in the venturi water scrubber. Because of the scrubbing the water content of the gas drops from 34.4 mole% to 21.5 mole%. After scrubbing the gas is compressed to 8.3 bar, this results in a temperature rise from 65°C to 309°C. The power necessary to drive the compressor is 1575.8 kW. After compression the gas is fed to the sulfur removal unit, where all the sulfur is removed (about 0.02 mole%). Then the gas is ready for conversion in the SOFC-GT hybrid system.

The gas is heated first to 475°C by the flue gas from the gasifier, before it is mixed with the anode recycle stream. The anode recycle stream is 60% of the flow leaving the anode of the fuel cell. This is done to make sure that the water content of the fuel gas is high enough for the internal reforming processes. Also carbon deposition at the anode, which can deteriorate the performance of the fuel cell [13], can be avoided by doing so. Two recycle blowers one at the inlet of the anode and the other at the inlet of the cathode are

installed to overcome the pressure drop of the fuel cell. The anode recycle blower requires 116.64 kW<sub>e</sub> and the cathode recycle blower 640.87 kW<sub>e</sub>.

The power consumption of the cathode recycle blower is higher since the cathode flow is much larger than the anode flow. The large cathode flow is necessary to cool the stack. The cathode recycle blower only compensates for the pressure drop of the SOFC stack. The compression of air from environmental pressure to the fuel cell stack pressure occurs in a compressor coupled to the gas expansion turbine. After compression the air is heated by the flue gas from the gas turbine exhaust. The calculated flow of fresh air is 19.24 kg/s. The heated air is mixed with the cathode recycle flow before it enters the recycle blower and the fuel cell. The cathode recycle is assumed to be 80% of the flow leaving the cathode of the fuel cell. The fuel cell operating at 750°C produces 24307.14 kW of electrical energy. Not all fuel is converted in the SOFC stack; the fuel utilization is 80%. The anode and cathode outlet flows are passed to a combustor, where the residual fuel is combusted. The resulting flue gas has a temperature of 940°C, which is also the inlet temperature of the gas turbine. The gas turbine is coupled to the air compressor and a generator through a shaft. The generator produces 4471.28 kW of electrical energy. Both flue gas flows, the flue gas flows from the gasifier and from the SOFC-GT hybrid system, contain a significant amount of heat. The heat extracted from the flue gasses in the heat recovery boiler is 17272.89 kW.

In table 5 the energy and exergy inputs, consumptions and efficiencies of the system for the conversion of biomass into electricity are presented.

The gross efficiency is calculated by dividing the total delivered gross electrical power by the total absorbed heat power. The net efficiency is calculated by dividing the total delivered net electrical power by the total absorbed heat power.

**Table 5 energy and exergy input, consumption and efficiency of the biomass gasifier and SOFC-GT hybrid system (without bottoming cycle)**

	No.	Source	Energy [kW]	Totals [kW]	Exergy [kW]	Totals [kW]
Absorbed power	1	Biomass	61261.93		69812.73	
Delivered gross power	G	Generator (GT)	4471.28	612961.93	4471.28	69812.73
	17	Fuel Cell	24307.14		24307.14	
				28778.41		28778.41
Aux power consumption	11	Compressor	1575.80		1575.80	
	16	Compressor	116.64		116.64	
	101	Pump	0.67		0.67	
	201	Compressor	344.87		344.87	
	253	Compressor	640.87		640.87	
				2678.85		2678.85
Delivered net power				26099.56		26099.56
Delivered heat	8	Heat Sink	6032.28		3637.28	
	23	Heat Sink	17272.89		10192.88	
				23305.16		13830.17
Total delivered				49404.73		39929.73
Efficiencies		Gross	46.976%		41.222%	
		Net	42.603%		37.385%	

The residual heat (from the sinks 8 and 23 in figure 2) is used to generate steam in the boilers of the bottoming steam cycle. The heat transfer of each of these sinks corresponds

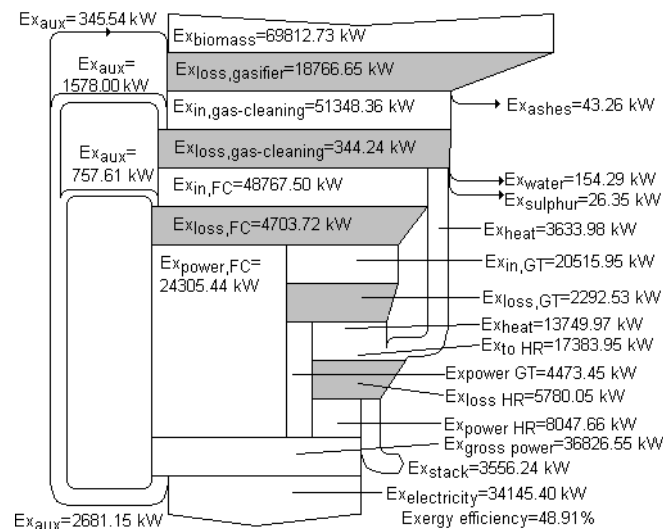


to the heat transfer in the boilers as modeled in figure 3. The boilers generate steam of 530°C at a pressure of 38.58 bar. The total amount of steam produced in these boilers is 7.54 kg/s. The steam is expanded in a turbine, which is coupled to a generator through a shaft. This results in an electricity production of 8113.00 kW. The power consumption of the pumps in the heat recovery system is 65.34 kW<sub>e</sub>. The net electricity production of the steam bottoming cycle is 8047.66 kW. The combined results of the bottoming cycle and the energy conversion system are presented in table 6. The efficiency is calculated by dividing the total delivered power by the total absorbed power (= biomass fuel power to the system).

**Table 6 energetic and exergetic efficiency of the total system including bottoming cycle**

	Source	Energy [kW]	Totals [kW]	Exergy [kW]	Totals [kW]
Absorbed power	Biomass	61261.93		69812.73	
			61261.93		69812.73
Delivered net power	SOFC-GT	26099.56		26099.56	
	Bottoming cycle	8047.66		8047.66	
Total delivered power			34147.22		34147.22
Efficiency	Total	55.740%		48.913%	

The exergy flow diagram of the total system (gasification SOFC-GT hybrid system with bottoming cycle) is depicted in figure 4. The grey blocks in this diagram indicate the process subsystems in which exergy is lost. The white blocks indicate the exergy transfer between the process subsystems. The bottoming cycle is indicated in the diagram by HR. The losses caused by the heat transfer from the producer gas and flue gas to the steam are included in the losses of the bottoming cycle.



**Figure 4 Exergy flow diagram of the total system**

## Discussion

From figure 4 it becomes clear that the gasification subsystem has the highest exergy losses. These losses are caused by the large irreversibilities of the combustion of the char in the combustor. The losses of the steam production and air preheat are also taken into account. The exergy losses during heat transfer are significant, because of the large temperature differences between the fluids which exchange heat. The system is designed such, that the gasifier can operate independently from the gas cleaning and/or SOFC-GT hybrid system. The exergy losses in the gas cleaning subsystem do not seem to be very



large, because the losses due to the heat transfer from the producer gas are not included here as they have been allocated to the bottoming cycle.

Table 6 clearly shows the difference between the energy efficiencies and the exergy efficiencies of the total system. This difference is actually caused by the difference between the lower heating value and the exergy value of the biomass.

The biomass gasification combined with SOFC-GT hybrid system is intended to be the reference system for future system design studies. The gasification technique used is chosen because of its relative high hydrogen content of the producer gas. Alternative gasification processes can be considered, for instance pressurized air gasification. Pressurized air gasification generates a producer gas diluted with a significant amount of nitrogen, but has the advantage that the gas is already pressurized; a hot gas cleaning system is easier to implement. On the other hand the nitrogen rich producer gas will affect the performance of the SOFC-GT hybrid system. Further system studies are necessary to show how this effects the overall efficiency.

The fuel cell temperature used here (750°C) is relatively low. Most current SOFC's operate at 900-1000°C, but the general trend is to lower the operating temperature of the fuel cell. The lower operating temperature will simplify the construction of the SOFC; they will reduce thermal expansion and corresponding stresses in the materials and will allow the application of more and cheaper materials. The gas turbine can be relatively simple because of the intermediate operating conditions. The low fuel cell temperature has only a limited effect on the overall efficiency of the system [1].

Further optimization the SOFC-GT hybrid system is conceivable of course. A more detailed evaluation of the anode and cathode recirculation, considering other ways to recirculate the gasses as well as the amounts of recirculation. By doing so, the overall efficiency of the process can be improved.

In this system is a relative simple steam cycle used as bottoming cycle. Further reductions of the exergy losses are conceivable but the optimization of the bottoming cycle is not the purpose of this project.

## References

- [1] K. J. Bosch, N. Woudstra, et al., Fourth International Conference on Fuel Cell Science, Engineering and Technology, 2006, p. 1.
- [2] H. Hofbauer, R. Rauch, et al., 12th European Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection, Amsterdam, The Netherlands, 2002, p. 1.
- [3] M. Bolhar-Nordenkamp, K. Bosch, et al., 1st International Ukrainian Conference on BIOMASS FOR ENERGY, Kiev, Ukraine, 2002.
- [4] M. Bolhar-Nordenkamp and H. Hofbauer, International Slovak Biomass Forum, Bratislava, 2004, p. 227.
- [5] A. V. Bridgwater, The technical and economic feasibility of biomass gasification for power generation, *Fuel* 1995; 74: 631.
- [6] S. C. Singhal, Advances in solid oxide fuel cell technology, *Solid State Ionics* 2000; 135: 305.
- [7] EG&G Technincal Services, Fuel Cell Handbook, Nation Energy Technology Laboratory, Morgantown, 2004.
- [8] C. N. Hamelinck and A. P. C. Faaij, Future prospects for production of methanol and hydrogen from biomass, *Journal of Power Sources* 2002; 111: 1.
- [9] M. V. Twigg, Catalyst Handbook, Wolfe Publishing Ltd., London, 1989.
- [10] Cycle-Tempo, TU Delft, Build: 5.0, 2006
- [11] H. Hofbauer, R. Rauch, et al., Expert Meeting on Pyrolysis and Gasification of Biomass and Waste, Strasbourg, 2002.

- [12] H. Hofbauer, R. Rauch, et al., 1st World Conference and Exhibition on Biomass for Energy and Industry, Sevilla, Spain, 2000.
- [13] K. M. Walters, A. M. Dean, et al., Homogeneous kinetics and equilibrium predictions of coking propensity in the anode channels of direct oxidation solid-oxide fuel cells using dry natural gas, Journal of Power Sources 2003; 123: 182.