

Energy Production from biomass gasification by molten carbonate fuel cells: process simulation

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This paper presents an integrated approach to the steady state simulation of biomass gasification, molten carbonate fuel cells (MCFC) and power generation processes. The software developed allows to study 'in silico' the effect of variations of the process conditions as well as modification of the input fuel, thus providing a useful tool for supporting technical decisions and feasibility study on the use of fuel cells in developing countries.

Keywords: molten carbonate fuel cells, computer simulation, biomass gasification.

1. Introduction

Deregulation of the electric power industry and more stringent emission controls are stimulating investments into fuel-cell systems. The application of fuel cells is particularly attractive in the renewable energy arena: biomass could be used as fuel for the hydrogen production, thus addressing the problems of generation of carbon dioxide at the same time. This topic is also of interest to developing countries for off-grid power generation with low impact to the environment. Among the different fuel cells developed so far, molten carbonate fuel cells (MCFC), also referred to as "second generation" cells (Kraaij et al., 1998), have been deeply investigated in the last decade for several advantages with respect to other technologies. Since natural gas is the most used fuel in fuel cells, the use of biomass as fuel introduces many differences in the process. This is mainly due to the strong difference in the composition of the gas fed to the fuel cell. The main differences are (i) the external reforming is less important since the gas out from the gasifier contains only a few per cent of methane, (ii) the gas out from the gasifier needs to be cleaned from impurities and (iii) heat is produced in the gasification at higher temperature (850-900°C), underlining the importance of a good heat integration and recovery. This paper presents a steady state model for the simulation of a biomass gasification and energy production in molten carbonate fuel cells. The model presented develops from the simulation of an Ansaldo Fuel Cell process (De Simon et al., 2003) and contains all the necessary modifications to adapt the model to the gasification of biomass.

2. Model Development

A fully distributed bi-dimensional open loop model was already developed for a MCFC (De Simon et al., 2003). Chemical and electrochemical reactions are considered in the

model: see Fermeglia et al. (2005) for the details of the reactions involved and for the geometry of the cell and the stack.

The process flow diagram is shown in figure 1. The biomass is fed into a fluidised bed gasifier unit together with steam and oxidant (air enriched in oxygen up to 95%). The solid separated in the cyclone is sent to a combustor where the unreacted char is burned and the heat produced is partially recycled into the system and partially used for cogeneration purposes. The producer gas with a temperature around 870°C is cooled to obtain a temperature suitable for the rest of the process and is sent to a circulating fluidised bed tar cracker with dolomite as a catalyst. The cracking reactor temperature is kept at 450°C by internal cooling with air used for the char combustion. The temperature reduction allows the alkali metals and residual uncracked tars to condense on the dolomite particles. The exiting gas is almost free of C₂+ hydrocarbons and is composed primarily of CH₄, H₂, CO, CO₂ and H₂O. Next it is further cleaned from sulphur and from fine entrained solid particles. These units are not able to withstand temperature higher than 450°C, therefore the cracking low temperature is justified again, even if higher temperature gains higher tar conversion (Lopamudra et al, 2005).

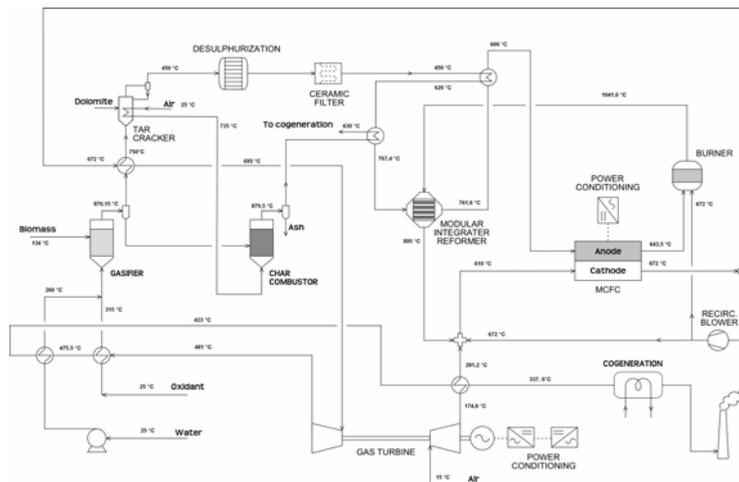


Figure 1: process flow diagram.

The gas is heated again and sent to the compact reformer for converting part of the methane and water. It consists of plates and frames heat exchanger with one side filled with reformer catalyst. The heat required by the reaction is supplied by the gas flowing in the other side of the exchanger. The reformed gas is cooled down to 600°C and fed to the anode of the fuel cell stack where further hydrogen is produced. Part of the fuel is not consumed in the anode to avoid diffusion controlled electrochemical reaction and because the stack is not able to process CH₄. The residue fuel is burnt with part of the cathode exhaust recycle, giving the heat necessary for the reformer and is mixed with fresh air from the compressor and the other part of the cathode exhaust recycle before entering in the cathode. The cathode recycles are needed for (i) keeping the fuel cell stack inlet temperature at about 600°C, (ii) keeping the flow at a suitable rate for the

thermal management of the stack and (iii) supplying the carbon dioxide needed for the electrochemical reaction.

The exhaust not recycled, after exchanging heat with the producer gas, is sent to the gas turbine for expansion and power production. The flue gas heats the oxidant, evaporates the water for gasification and heats the compressed air in the regenerator. The residual heat is used for cogeneration purposes.

The **gasifier** is modelled with a simplified model. For known input composition, temperature of the producer gas, proximate and ultimate analysis and HHV of the biomass, it calculates the mass and heat balance of the unit. The input data are taken from (Lau et al. 2002). The model of the **clean-up system** is simply a unit that removes all the impurities to levels compatible with the reforming and the fuel cells. There's no energy related influence of this unit to the system. Likewise the gasifier, also a **fuel cells** stack model wasn't available in the library of units of the simulator used. In this case the user model developed in (De Simon et al., 2003) was employed, interfacing the Fortran 90 code with the process simulator. The parameters required by the simulation code are based on Ansaldo Fuel Cells experimental tests. The number of cells in the stack are fixed and biomass feed rate is varied to keep the hydrogen and carbon monoxide utilization at about 75%; the cell surface and the stack current are fixed. Also for the **reformer** no predefined unit was available in Aspen PlusTM libraries, so an approximating scheme using standard units has been adopted. The pressure drop of the various devices (except for the fuel cells) has been neglected and an estimation of the total heat losses to 3% of the HHV of the biomass feed is used.

3. Results and discussion

The model developed is used for the simulation of 3 different biomass feed conditions: (i) sugarcane bagasse (BG) which is a residue from sugar cane treatment, (ii) switchgrass (SW) and (iii) nut shells (NT) which is a mixture of 20% nut shell, 40% hazel nut shell and 40% wood. Table 1 reports the ultimate and proximate analysis of the three feeds and the moisture (Lau et al. 2002).

Table 1: biomass properties; data from (Lau et al. 2002).

		BG	SW	NT
Proximate analysis	Ash	6.99	5.24	2.38
	Volatile Subst.	80.06	80.09	76.28
	C residual	12.95	14.67	21.34
	HHV (MJ/kg)	17.77	18.62	19.80
	Moisture	20%	12%	12.5%
Ultimate analysis	C	46.46	47.73	48.51
	H	5.40	5.56	5.65
	N	0.18	0.67	0.77
	S	0.06	0.01	0.01
	Ash	8.50	4.60	3.07
	O	39.36	40.68	41.98
	Cl	0.04	0.11	0.01

Table 2: general simulation input data

Gasifier input data		Stack input data		Input efficiency	
T gasifier (°C)	870	Fuel util.	75%	Turbine entr. efficiency.	0.85
Pressure (bar)	3.5	T anode (°C)	600	Turbine mech. efficiency	0.97
Oxidant power consumption kWh/Nm ³ O ₂	0.4	T cathode (°C)	600	Compressor entr. efficiency	0.77
O ₂ /C (mol/mol) (*)	0.28 for BG 0.18 for NT 0.23 for SW	Pressure (bar)	3.5	Compressor mech. efficiency	0.97
H ₂ O/ C (mol/mol) (*)	0.4 for all	Active surf (m ²)	0.711		
T clean up (°C)	450	Current (A)	1100		
		N.of cells	2850		

(*) O₂/C it's a molar ratio between the oxygen fed to the gasifier and moles of carbon in the biomass

Table 3: simulation results

		BG	SW	NT
Process Data	Biomass feed rate (kg/h)	1900	1550	1450
	HHV (MJ/Kg dry)	17.77	18.62	19.8
	MW	7.5	7.05	6.97
	Oxygen feed rate(kg/h)	552	429	321
	Water feed rate (Kg/h)	424	391	369
	Gasifier cold efficiency ⁽⁺⁾	76.5	82.8	84.5
	Cracking power gain (MW) ⁽⁺⁾	0.73	0.65	0.63
	CH ₄ ref conversion (%)	86.8	85.5	84.5
	Reforming power gain % ⁽⁺⁾	14.8	14	13
	STACK RESULTS	T max single cell (°C)	686	681
T min single cell (°C)		625	622	624
Average solid T (°C)		654	648	651
V (V)		0.733	0.773	0.746
Power (kW)		2299	2424	2341
Efficiency HHV (%) ⁽⁺⁾		38.0	39.5	38.2
Efficiency LHV (%) ⁽⁺⁾		42.1	43.5	42.0
NET VALUES AND EFFICIENCIES		Net electrical power (MW)	2739.5	2841
	Net thermal power (MW)	2398.5	2035	2072
	Electrical efficiency % ⁽⁺⁾	36.5	40.3	40.2
	Cogenerative efficiency % ⁽⁺⁾	68.4	69.1	69.85

(+) see the definitions hereafter listed

The three different feeds are simulated with the process conditions reported in table 2. Table 3 shows the simulated results for the biomasses considered. The parameters used

to characterize the results are defined as follows. The cracking power gain is the HHV of the tar in the producer gas that is recovered by cracking in form of CH₄, H₂. The reforming power gain is the percent gain calculated on a basis of HHV of the gas entering in reforming unit. The gasifier cold efficiency is calculated as : $\frac{HHV_{\text{prod gas}}}{HHV_{\text{bm}}}$ where bm is the type of biomass. The stack power efficiency HHV is calculated as: $\frac{Stack\ Power}{HHV_{H_2} + HHV_{CO}}$, the stack power efficiency LHV as: $\frac{Stack\ Power}{LHV_{H_2} + LHV_{CO}}$. The

electrical efficiency: $\frac{Net\ Electric\ Power}{HHV_{bm}}$ and the cogenerative efficiency: $\frac{Thermal + Electric\ Power}{HHV_{bm}}$.

The results obtained for the gasifier are compared to experimental data of gasification of similar biomasses and there is a general good agreement between the experimental and the simulated data.

As shown in Table 3, the gasifier cold efficiency is in the range of 75-85%, therefore, in the first part of the process about 20% of the chemical energy of the fuel becomes heat, underlining the importance of the thermal management in the subsequent part of the process. The best way to recover this heat is at the reformer: the reactions are endothermic and they convert heat into chemical energy of the hydrogen and CO produced; this chemical availability is then converted into power in the fuel cell with a high efficiency. The HHV rise obtained in the reforming is about 14%, and is transformed in power in the fuel cell stack with the efficiency of about 42%. Consequently, the net electric power recovered for reforming is almost 6% of the producer gas, even if its methane content is not very high (8-9% mol/mol, see table 2).

Heat produced by gasification is also recovered by turbine expansion. The heat quality of the producer gas is the highest of the process (870°C), hence it is possible to exchange it with the gas to be expanded. The temperature difference is only 20-25°C because the high heat capacity difference between the two fluids. The high flow rate of the turbine inlet fluid is necessary for the high flow rate at the cathode and the fixed temperature of the cathode inlet. High flow rate requires high gas recycle and this requires high fresh air input to keep the temperature at 600°C. Another important energy related remark involves the cracking power gain (see table 3), which represents about 10% of the HHV of the feed biomass.

Comparing the three feedstocks considered, the net electric efficiency is similar for switchgrass and nutschell (about 40%), not so for bagasse that reaches only 36,5%. The gasification efficiency for bagasse is 76.5%, for switchgrass and nutshell it is 82.8% and 84.5% respectively. Therefore, for constant hydrogen and carbon monoxide fed into the anode, in the bagasse case an higher feed rate is necessary, producing a poorer gas. The cogenerative efficiency in all the cases is not very high (less than 70%), due to the thermal dilution caused by the high fresh air flow rate.

An analysis of table 3 shows clearly that, at almost constant conversion at anode and total electrical power, the electrical and cogeneration efficiency of the different biomasses are similar but a much lower flow rate is used in the case of nut shell biomass, which is directly related to the higher heating power of this biomass.

The electric efficiency is in the range of 36-40% depending on the type of biomass considered. In other studies (Kivisaari et al. 2002) similar results has been found. In (Kirill et al. 1998) an efficiency of 53% was calculated, for a hybrid system based on double fluidised bed reactor (gasifier-combustor), internal reforming MCFC and a complex steam turbine cycle.

4. Conclusions

This paper presented the development and the implementation of a model based on Aspen PlusTM for the steady state simulation of a MCFC and power generation processes coupled with the gasification of biomass. The paper reports results of computer simulation for a realistic configuration of power generation system by MCFC, focusing on macroscopic quantities of interest. The model has been applied to three different biomasses allowing us to compare the performances of the different feeds and to understand the details of the entire process. The results of the simulation presented allow us to take the following conclusions. The efficiency obtained by coupling the biomass gasifier and the MCFC is around 36 – 40 %, depending upon the biomass used: considering the low performances of the biomass as fuel the efficiency obtained indicates that the energy production process by using fuel cells is feasible. In the gasification process a lot of valued heat is produced (20% of the total input HHV at 870°C), underlining the importance of the thermal integration in the process. The producer gas tar energy content is about 10% of the total biomass HHV, thus showing the importance of a cracking to recover tar heating value. The endothermic reforming is able to convert thermal energy into chemical one; at the same time it increases the hydrogen and carbon monoxide availability for the fuel cell stack. By means of the reforming, 6% of the biomass HHV becomes electricity.

Among the three biomass considered, the bagasse permit the lowest electric efficiency because of its difficulties in being gasified, performing the worst gasification cold efficiency and then the lowest fuel content in the producer gas.

5. References

- De Simon, G., F. Parodi, M. Fermeglia, R. Taccani, 2003, *J. P. Sources*, **115**, 210-218.
- Fermeglia M., A. Cudicio, G. De Simon, G. Longo, S. Pricl, 2005, *Fuel Cells*, **5**, 66-79.
- Kivisaari T., Björnbohm P., Sylwan C., 2002, *J. P. Sources*, **104**, 115-124.
- Kirill V. Lovachyov, Horst J. Richter, 1998, *Energy Convers. Mgmt*, **39**, 1931-1943.
- Kraaij, G. J., G. Rietveld, R. C. Makkus, J. P. P. Huijsmans, 1998, *J. P. Sources*, **71**, 215-217.
- Lau F. S., Bowen D. A., Dihu R., Doong S., Hughes E. E., Remick R., Slimane R., Turn S. Q., Zabransky R., 2002, *Techno-Economic Analysis of H₂ Production by Gasification of Biomass*, report of the DOE contract DE-FC36-01GO11089.
- Lopamudra Devia, Krzysztof J. Ptasinska, Frans J.J.G. Janssena, Sander V.B. van Paasenb, Patrick C.A. Bergmanb, Jacob H.A. Kielb, 2005, *Ren. Energy*, **30**, 565-587.