



A Thermodynamic Approach to the Integration of a Sugar Cane Bagasse Gasifier with a Solid Oxide Fuel Cell

Luis E. Arteaga-Pérez^{*a}, Yannay Casas-Ledón^b, Raul Pérez-Bermúdez^c,
Lizet Rodríguez-Machín^c, Luis M. Peralta-Suárez^a, Ronaldo Santos^a,
Jo Dewulf^b

^aChemical Engineering Department. Central University of Las Villas. Road to Camajuaní Km 5.5. Santa Clara, c/p 54830, Villa Clara, Cuba.

^bResearch Group ENVOC, Ghent University, Coupure Links 653, 9000 Ghent, Belgium

^c Mechanical Engineering Department. Central University of Las Villas. Road to Camajuaní Km 5.5. Santa Clara, c/p 54830, Villa Clara, Cuba.

luiseap@uclv.edu.cu

The thermo-conversion of liquid and solid biomass resources is becoming one of the best alternatives for waste solids reuse and green energy production, especially for developing countries. The proposed methodology allows the thermodynamic and electrochemical modeling of sugar cane bagasse gasification (B-G) coupled to a medium temperature solid oxide fuel cell stack. The validation of the models is carried out using pilot plant data for two biomass sources: sugar cane bagasse and rice peel. The synthesis gas composition, LHV and HHV are determined as well as the fuel cell power output and systems performance evaluated. After model validation the solid biomass gasification is studied for waste sugar cane bagasse, varying: the air factor (0.25-0.4) and air preheating (120 °C – 250 °C). The fuel cell utilization coefficient is fixed (FUC = 0.75), in this way the depleted gases from the stack can be used in an after combustor to produce energy for the B-G otherwise an overall efficiency penalty is superimposed to the system. The best results are obtained at 150 °C of preheating temperature and 0.30 excess of air in the gasifier at which the system efficiency is 74.3 %. The HHV (ranging from 2.82 MJ/kg to 4.08 MJ/kg) and LHV (2.66 MJ/kg to 3.84 MJ/kg) of the gasification gasses produced from sugar cane bagasse are similar to those reported for other biomass sources.

1. Introduction

In the present days the energy and the environmental security are the main concerns in the policies of any country. With the increase in the energy demand, biomass derived fuels conversion has drawn great attention not only by their environmental compatibility but also as an alternative route to mitigate the market floating value of the fossil fuels. The main processes to convert solid biomass into a rich energy gas are: Combustion, Pyrolysis, Gasification and Liquefaction (Quakk et al., 1999). In the present paper we focused the interest on the thermodynamics of biomass gasification technology. Biomass gasification is a process which involves the transformation of carbonaceous materials into a gas and waste solids. This process allows fractionating a hard handling solid into a multicomponent flexible gas which can be easily purified and converted into a clean fuel or into a synthetic base to obtain chemicals in a biorefinery (Nag, 2008). Gasification takes place when air, oxygen, steam or water are reacted with the carbon contained in biomass. The gases produced by gasification technologies are known as gasification gases (GG) and have been tested in various applications such

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as: gas turbines, combined cycles, chemicals production and more recently as feedstock for high efficiency fuel cells. The energy quality of the produced gas varies depending on the oxidant and process conditions. When the gasifier is operated with pure oxygen the energy quality of the gas (HHV=10 - 18 MJm⁻³) is more than twice the produced when the reactor runs on air. Partial combustion is necessary because it supplies the heat required by the endothermic reactions. The gasification gas of biomass is composed of H₂, CO, CH₄, C_xH_y, CO₂ and N₂. The main concern in the process is to minimize the formation of TAR. An alternative to upgrade the hydrogen content in the gas and to reduce the TAR formation is to operate the reactor with a mixture of steam and air. Various authors have proposed different reaction schemes to describe the reaction system (Basu, 2010; Doherty et al., 2009). The suitable integration of fuel cells with gasification reactors is limited by the gas composition and process conditions. In recent years, the solid oxide fuel cells (SOFC) running on pure hydrogen or synthesis gas has drawn a great attention, due to its application in distributed power systems. Among the various types of fuel cells the SOFC have many distinctive characteristics such as high efficiency in energy conversion, modularity, environmental compatibility, support internal reforming and water gas reactions, no need of noble materials as electrodes and the high operating temperatures of SOFC (600 °C – 1,000 °C) allows the cogeneration and heat reuse (Arteaga et al., 2009). In the present paper the simulation of a biomass gasification unit integrated to a medium temperature solid oxide fuel cell is carried out. The feasibility of the operation is evaluated for different operation scenarios. The gasification model is validated using pilot plant data.

2. Experimental

The pilot plant is installed at the thermal energy department of the UNICAMP in Brazil. The gasification section comprises a carbon steel atmospheric fluidized bed gasifier with 0.92 m OD. The nominal capacity of the reactor is 100 kg/h of solid biomass. The gas after the analyzer is burned in a flare unit. The formation of TAR is computed with an isokinetic sond. Previous experiments a biomass characterization was developed for the two sources.

The following variables were controlled in the experimentation:

- The air flow was calculated on the base of the excess factor, defined to minimize the TAR formation between 0.28 and 0.4.
- The temperature of the gases leaving the reactor.

The composition of the gases was measured with a GC90 equipped with a TCD and Porapak Q.

3. Processes flow diagrams

3.1 Biomass Gasification

Figure 1 shows a schematic of a biomass gasification train.

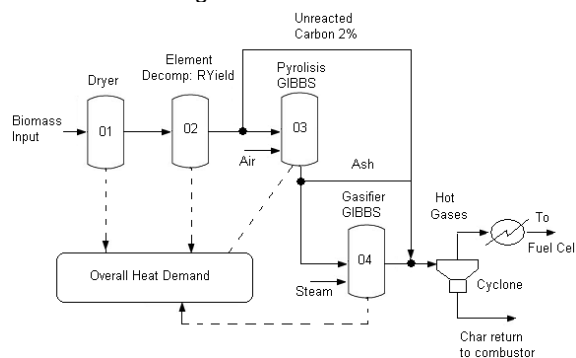


Figure 1. Aspen Plus modeling flowsheet for gasification

It consists of a biomass fed system which comprises: an air compressor, a storage recipient, a GLP burner and a screw. The gas composition exiting the reactors is adjusted using the temperature equilibrium restrictions approach to set equality between experimental and model results.

3.2 Solid oxide fuel cell

The SOFC model represented in Figure 2 is used to study the process. The fuel coefficient in the fuel cell is used to estimate the hydrogen flow needed to fulfill the energy demand and in-situ methane steam reforming is considered in the fuel cell anode. Usually the heat consumed in the gasifier is obtained by the combustion of GLP or a fraction of the gasification gas, but here the gases leaving the anode are used to fulfill this energy demand.

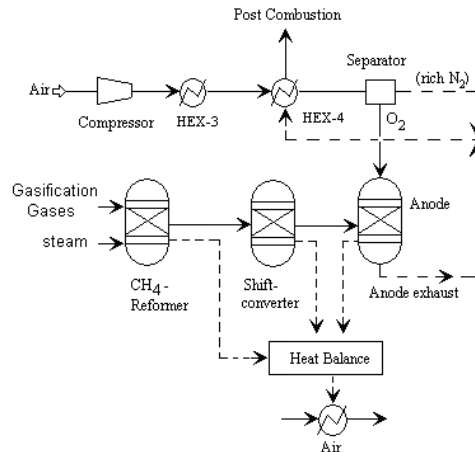


Figure 2. Solid Fuel cell performance model

4. System modelling

4.1 Gasification model

All systems were modeled in Aspen Plus process simulation software. In all cases the RKS cubic equation of state method was used for the properties estimation. Biomass was treated as a nonconventional solid with known PSD. The thermal losses in the gasifier and un-reacted coke were assumed as 3 % and 4 % respectively. It is assumed steady state calculations, zero dimensional model, drying and pyrolysis are instantaneous and carbon is assumed as conventional solid. The efficiency in the cyclone is set at 80 %. A FORTRAN block is used to split the biomass stream into its elements involving a variation in the enthalpy calculated by a RYield block. The gas composition exiting the reactors is adjusted using the temperature equilibrium restrictions approach to set equality between experimental and model results.

4.2 Model of a solid oxide fuel cell

The cell anode is simulated as a series of kinetic, equilibrium and conversion reactors. Since the S/C ratio of the gasification gas fed into the anode varies, a steam stream is used to control this parameter and avoid carbon deposition problems. The insitu methane reforming is studied using a kinetic reactor model which considers a power law pattern with a negative reaction order for water (Nagel et al., 2008). Moreover, the shift conversion of the carbon monoxide is simulated using a Gibbs reactor model (*equilibrium*). The air flow is brought to operating pressure and temperature using (*Compressor and Heatx*) blocks. The oxygen consumed in the electrochemical reaction is separated from the air using a (*Separator*) block and the inlet flow of air is calculated for an oxygen stoichiometry of 2, representing a utilization of 50 %. Considering the results reported in a previous paper (Arteaga et al., 2009), the fuel utilization coefficient is fixed at 75 %. The heat balance in the cell considers the heat consumed in the methane reforming and the heat produced by the electrochemical reaction and shift conversion.

5. Parameters definitions.

The gasification gases composition, fuel cell power output, the gasifier power, the heating values of gasification gases and system efficiency are the main answer parameters used in this research as a measure of process feasibility. The following definitions are used:

$$\text{Cell power: } P_{\text{cell}} = I_{\text{cell}} \times V_{\text{cell}} \quad (1)$$

$$\text{System thermal efficiency: } \eta_s = \frac{(P_g + P_{\text{cell}} - W_c)}{(m_{\text{Biomass}} \times \text{HHV}_B)} \quad (2)$$

Where: P_{cell} is the fuel cell power (kW), P_g is the gasifier power (kW), W_c is the work consumed by compressor and m_{Biomass} , is the flow of bagasse (kg/s). The low and high heating values of gasses are calculated considering the individual contributions of all components (See Table 1). The influences of air factor, steam injection and oxidant temperature are the independent variables in this study.

6. Results and Discussion

6.1 Model Validation

The pilot scale experimental results obtained at the above described conditions were used to validate the gasification model. The input data in all the calculations involves the biomass proximate and ultimate compositions and air factor (air fraction above the stoichiometric). Four experiments were used to assess the theoretical accuracy, and the highlighted rows in Table 1 represent the model results. The critical elements in the comparison are the hydrogen, methane and carbon monoxide.

Table 1. Experimental pilot scale results of the rice peel and sugar cane bagasse gasification.

| Biomass | Air Factor | TGG (°C) | CO (%) | CH ₄ (%) | H ₂ (%) | CO ₂ (%) | O ₂ (%) | N ₂ (%) | HHV (MJ/kg) | LHV (MJ/kg) |
|-----------|------------|----------|--------|---------------------|--------------------|---------------------|--------------------|--------------------|-------------|-------------|
| Bagasse | 0.28 | 732.5 | 18.32 | 5.01 | 5.72 | 16.34 | 0.49 | 54.12 | 4.08 | 3.84 |
| | 0.28 | 730 | 18.02 | 5.13 | 5.56 | 11.88 | 0.50 | 58.91 | 4.17 | 3.92 |
| | 0.34 | 803.5 | 15.94 | 3.56 | 5.05 | 15.62 | 0.45 | 59.38 | 3.28 | 3.10 |
| | 0.34 | 803 | 13.86 | 3.57 | 4.79 | 16.59 | 0.46 | 60.73 | 3.16 | 2.97 |
| Rice peel | 0.28 | 732.5 | 18.21 | 4.09 | 5.75 | 16.49 | 0.34 | 55.12 | 3.77 | 3.56 |
| | 0.28 | 729 | 18.05 | 3.96 | 5.93 | 17.50 | 0.31 | 54.25 | 3.43 | 3.24 |
| | 0.34 | 801.5 | 16.18 | 3.54 | 5.4 | 13.67 | 0.72 | 60.49 | 3.38 | 2.19 |
| | 0.34 | 801 | 15.13 | 3.64 | 5.17 | 11.37 | 0.7 | 63.99 | 3.20 | 3.01 |

The increment of the air factor reduces the concentration of the components which contribute to the gas heating value (CO, H₂, CH₄). The gas heating values varies 2.10 MJ/kg for a little change in the air excess 12 % for bagasse and 1.0 MJ/kg for rice peel. This effect can be explained due to the excess in air favors the partial combustion reactions. For the experimental runs, the fuel flow was set at 80 kg/h and 1 atm as gasification pressure. As can be noticed, the model predictions are in good agreement with the experimental results for both: the bagasse and rice peels. The differences in the HHV and LHV of GG are mainly due to the variations of compositions in CH₄ and H₂, similar results were reported for hemlock. For example in the extreme cases the CH₄ in bagasse gasification is over predicted with 0.12 % and H₂ value is 0.26 % under the experimental result. For rice peel the H₂ is over specified by 0.27 %. The models published by Doherty et al. (2009) and by Li et al. (2004) reported a similar behavior. In the present paper the differences between experimental and theoretical HHV of GG for bagasse are not critical and allows using the model to develop the sensitivity studies reported here below.

6.2 Model Application

The values of the air factor are set in the range where low levels of TAR were measured at the experimental conditions. The input data for the model is kept the same for model validation.

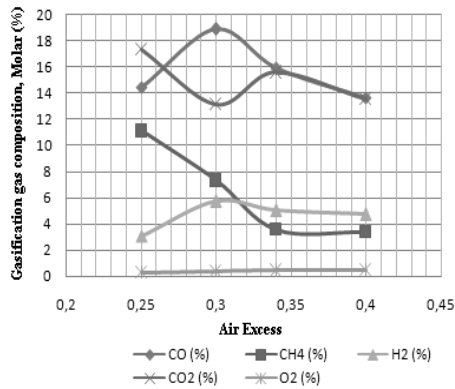


Figure 3. Effect of air factor on GG composition

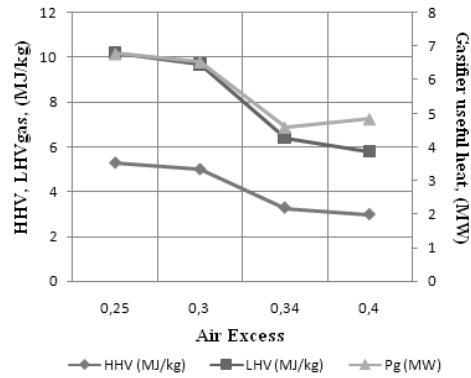


Figure 4. Effect of air factor on GG quality and gasifier power

In Figure 3 there are three elements of relevance: CO, CH₄ and H₂. The behavior of CH₄ and hydrogen are proportional and this can be explained by the reforming reaction and also by the equilibrium of the water gas shift. For air factors between 0.25 and 0.34 the methane concentration falls. At air factors above 0.34 the conversion of methane becomes to form a plateau, a similar behavior was reported by Li et al., (2004), but at values above 0.40 the methane is totally converted. The HHV of gasification gases is similar to those reported for other biomass sources (Yang et al., 2010) with the additional advantage that no NH₃ neither H₂S are formed during the conversion of sugar cane bagasse (Figure 4). The preheating of air favors the ratio CO/H₂ and the conversion of methane. A rise in the gasifier power output is exhibited for the explored range. Even when the figures 5 and 6 seem to suggest the operation at high temperature the real picture is rather different because the heat consumption to preheat the air conform an efficiency penalty.

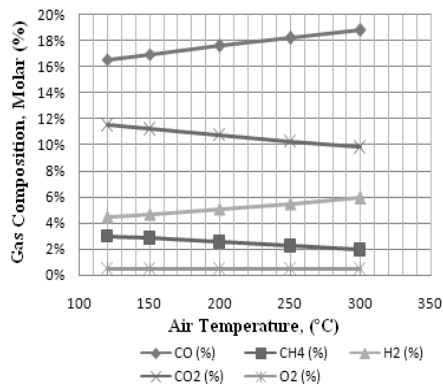


Figure 5. Effect of air preheating on GG composition

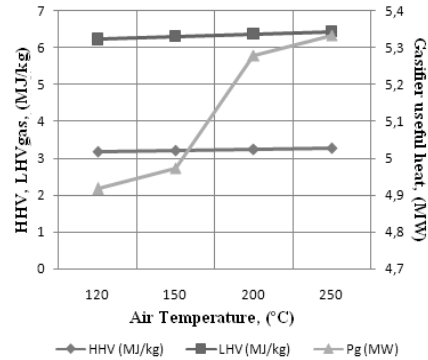


Figure 6. Effect of air preheating on GG quality and gasifier power

A variation of 70 % in the net heat is exhibited in the range of 120 °C to 250 °C it is recommended to operate at 150 °C in this way a balance between heat consumption, power production and system efficiency is established. The main factors affecting the system efficiency (Figure 7 and 8) are the gasifier useful power, the air compression work and the fuel cell performance which are directly proportional to the air excess and temperature.

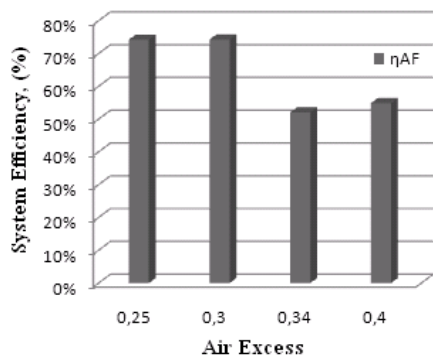


Figure 7. Effect of air factor on system efficiency

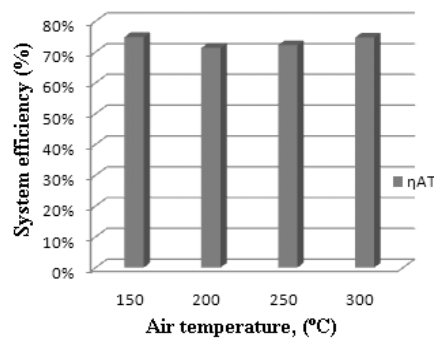


Figure 8. Effect of air temperature on system efficiency

For the studied conditions a flow of steam was used to maintain the moisture in the cell electrodes (~20 %) because the content of water in the GG is not enough to fulfil the cell requirements. The level of hydrogen and methane in the GG allows the operation of a fuel cell stack to produce between 300 kW and 450 kW. At 150 °C of preheating air and 30 % excess of air in the gasifier the system efficiency is 74.3% (Figure 7 and 8). Nevertheless the present study does not take into account the energy integration and heat losses in the fuel cell which can influence in the results here presented.

7. Conclusions

A thermochemical model was developed to describe the operation of a fluidized bed biomass gasifier. The model was validated against experimental pilot plant data and the results satisfy the accuracy needed to use it to extrapolate the operational conditions. The integration of a biomass gasifier and a solid oxide fuel cell is carried out and it was established that the air factor (30 %) and temperature (150 °C) have a great influence on the system performance ($\eta_{\text{sys}} = 74.30\%$). In a future study the fuel cell performance will be deeply analysed and evaluated for different fuel utilization coefficient and cell temperatures. Moreover the electrical efficiency of the fuel cell will be studied and compared with a combined cycle gas turbine.

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