THERMODYNAMIC EFFICIENCY ANALYSIS OF GASIFICATION OF HIGH ASH COAL AND BIOMASS

Rodolfo Rodrigues, Nilson R. Marcilio, Jorge O. Trierweiler
Department of Chemical Engineering. Federal University of Rio Grande do Sul (UFRGS).
Rua Eng. Luis Englert, s/n – Campus Central. 90040-040. Porto Alegre, Brazil. Phone: +55 51 3308 3956.
E-mail: rodolfo@enq.ufrgs.br, nilson@enq.ufrgs.br, jorge@enq.ufrgs.br

Marcelo Godinho
Department of Chemical Engineering. University of Caxias do Sul (UCS).
Rua Francisco Getúlio Vargas, 1130. 95070-560. Caxias do Sul, Brazil. Phone: +55 54 3218 2100.
E-mail: mgodinho@ucs.br

Abstract: Since the coal is one of major source of energy it is predicted that will continue to play an important role in the world energy demands. Although as a fossil resource, i.e. a non-renewable resource, that should take into account atmosphere emissions. Recently, the gasification has proven to be very promising to enable the conversion of carbon-based fuels for applications in synthesis and co-generation. In this sense, the joint processing of coal and renewable carbon-based fuel (biomass) allows to use coal in a cleaner way. This work evaluates the gasification potential of coal and biomass available in Brazil. For that a thermodynamic approach is used. High ash coal and biomasses of bigger energetic potential for co-generation are evaluated. Predictions evaluate the process performance through the estimation of efficiency by changing operational conditions, concerning the gasifying agent (air and steam). The preliminary results show the range of 70 to 80% efficiency by using only air as gasifying agent with up to 65% of stoichiometric air demand. On the other hand, using air and steam those values can reach 85% to close to 100% with smaller than 40% of stoichiometric air demand.

Keywords: gasification, high ash coal, biomass, cold gas efficiency, equilibrium model

1. INTRODUCTION

Since the coal is one of major source of energy it is predicted that will continue to play an important role in the world energy demands. Although as a fossil resource, i.e. a non-renewable resource, that should take into account atmosphere emissions.

The gasification is a technology for thermal processing of coal. Recently, this technology has proven to be very promising to enable the conversion of carbon-based fuels into products for applications in synthesis and co-generation. In this sense, the joint processing of coal and renewable carbon-based fuel such as biomass allows to use coal in a cleaner way. This technology called co-gasification leads to make up deficiencies of one kind of fuel by a combination with other fuel (synergy).

This work evaluates the gasification potential of coal and biomass available in Brazil. For that a thermodynamic approach is used through thermodynamic equilibrium model.

2. EVALUATION METHODOLOGY

Brazilian coal reserves are about 7 billion tons (0.8% of world total). The coal is subbituminous and high ash content (nearly 50%) [1]. On the other hand, the main Brazilian biomasses of bigger energetic potential to co-generation [2] are evaluated.

According to processing characteristics, the biomasses are here classified in three groups: agricultural, forestry, and industrial residues. For this study, rice husk [3] and coconut residue [4] are considered in the agricultural group. In the forestry group is considered sawmill wood waste [5] and in the industrial group are considered sugar cane bagasse [6], sugar cane straw [6] and footwear leather waste [7].

The proximate and ultimate analyses for six biomasses and high ash coal are presented in Tab. 1.
Table 1. Characterization of the fuels considered in this study.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture (wb)</td>
<td>11.7</td>
<td>12.00</td>
<td>83.74</td>
<td>12.93</td>
<td>50.20</td>
<td>29.40</td>
<td>14.10</td>
</tr>
<tr>
<td>Volatile matter</td>
<td>18.7</td>
<td>67.80</td>
<td>70.61</td>
<td>86.48</td>
<td>79.90</td>
<td>83.30</td>
<td>77.30</td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>25.1</td>
<td>13.60</td>
<td>19.14</td>
<td>12.93</td>
<td>18.00</td>
<td>12.80</td>
<td>16.90</td>
</tr>
<tr>
<td>Ash</td>
<td>56.2</td>
<td>18.60</td>
<td>10.25</td>
<td>0.59</td>
<td>2.20</td>
<td>3.90</td>
<td>5.80</td>
</tr>
</tbody>
</table>

Ultimate analysis (% wt, db)

<table>
<thead>
<tr>
<th>C</th>
<th>31.6</th>
<th>38.30</th>
<th>48.23</th>
<th>50.91</th>
<th>44.60</th>
<th>46.20</th>
<th>50.72</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>2.1</td>
<td>4.00</td>
<td>5.23</td>
<td>6.13</td>
<td>5.80</td>
<td>6.20</td>
<td>8.76</td>
</tr>
<tr>
<td>N</td>
<td>0.7</td>
<td>0.50</td>
<td>2.98</td>
<td>0.23</td>
<td>0.60</td>
<td>0.50</td>
<td>12.78</td>
</tr>
<tr>
<td>O</td>
<td>8.3</td>
<td>38.60</td>
<td>33.19</td>
<td>42.14</td>
<td>44.50</td>
<td>43.00</td>
<td>25.40</td>
</tr>
<tr>
<td>S</td>
<td>1.1</td>
<td>–</td>
<td>0.12</td>
<td>–</td>
<td>0.10</td>
<td>0.10</td>
<td>1.88</td>
</tr>
<tr>
<td>Cl</td>
<td>&lt;0.007</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.02</td>
<td>0.10</td>
<td>0.46</td>
</tr>
</tbody>
</table>

HHV (kJ/kg, db)

| 11.900 | 15.491 | 22,807 | 20,100 | 18,100 | 17,400 | 18,448 |

wt = weight, db = dry base, wb = wet base.

This study applies a thermodynamic equilibrium model for multiphase to evaluate the coal and biomass gasification. The proposed model finds the final composition minimizing the total Gibbs energy of an ideal mixture [8]. The model assumes one solid-phase consisting of solid carbon and one gas-phase consisting of 70 species (combinations of C, H, O, N, S, and Cl elements).

The simulations have been carried out Python codes using Cantera libraries [9] and thermodynamic properties of Burcat's database [10]. Python and Cantera are free to use softwares and available for Windows (Microsoft Corporation) and Linux (The Linux Foundation) platforms.

Predictions evaluate the process performance through the estimation of efficiency by changing operational conditions, concerning the amount of gasifying agent per amount of feed fuel: air at 25°C and 1 atm, and steam at 200°C and 1 atm. The air amount is expressed by “equivalence ratio” (\( \phi \)) and the steam amount is expressed by “steam-to-carbon ratio” (stm). Equivalence ratio represents the ratio among oxygen fed per oxygen required to complete combustion (stoichiometric oxygen demand). The cold gas efficiency is used to measure the process performance.

3. RESULTS AND DISCUSSION

Sensitivity analyses for biomass and coal gasification are done to a range of operational process conditions. The next figures show the results apart for the six biomasses and high ash coal. The evaluation of cold gas efficiency for several operational conditions identifies the operating ranges to formation of fuel gas with highest heating value to each fuel. Equilibrium temperature is the attainable temperature for each operating point in adiabatic conditions.

Fig. 1 illustrates the evaluating parameters for agricultural residues. Rice husk (Fig. 1a-b) already attains higher than 75% efficiency by using only air as gasifying agent in 0.35 < \( \phi \) < 0.45 up to 80% in \( \phi \approx 0.4 \). The joint use of steam and air should raise efficiency to 90% in \( stm > 0.75 \) and lower air demand (\( \phi < 0.3 \)). While coconut residue (Fig. 1c-d) reaches lower efficiency and temperature values due to high moisture content (83.74%) that suggests further studies to evaluate a previous drying stage.

The sawmill wood waste (Fig. 2) has the particularity that the addiction of a steam fraction reveals no improvement in outcomes. So 80% efficiency might already be attained with only air as gasifying agent, equivalence ratio close to 0.35.
Figure 1. Cold gas efficiency (%) and equilibrium temperature (ºC) to agricultural residues for a range of operational condition (air and steam demand).

Figure 2. Cold gas efficiency (%) and equilibrium temperature (ºC) to forest residues for a range of operational condition (air and steam demand).
The analysis of Fig. 3 shows a region of $\phi < 0.4$ where there are not gasification reactions for the coal's case. This operational range represents 0% efficiency (Fig. 3a) and temperature lower than 25°C (Fig. 3b). From equivalence ratio about 0.65 it can achieve efficiency up to 70% using only air as gasifying agent. Hence, the progressive increment of steam-to-carbon ratio can increase efficiency to 95% with $stm$ around 0.75 and $\phi < 0.5$.

Figure 3. Cold gas efficiency (%) and equilibrium temperature (°C) to high ash coal for a range of operational condition (air and steam demand).

Fig. 4 shows the evaluate parameters for industrial residues. As well as coconut residues, sugar cane bagasse has high moisture content (50.2%) that make difficult to reach higher efficiency values adding a steam fraction (Fig. 4a-b). Sugar cane straw (Fig. 4c-d) attains over 80% efficiency from $\phi \approx 0.4$ equivalence ratio, and 90% efficiency could be attained with steam-to-carbon ratio higher than 0.5. Footwear leather waste (Fig. 4e-f) can attain about 70% maximum efficiency just for using air as gasifying agent in range of 0.5 to 0.55. Whereas the application of steam can increase efficiency to 90% from 1.0 steam-to-carbon ratio.

Figure 4. Cold gas efficiency (%) and equilibrium temperature (°C) to sugar cane bagasse.
(c) Cold gas efficiency (%) to sugar cane straw.  
(d) Equilibrium temperature (°C) to sugar cane straw.

(e) Cold gas efficiency (%) to footwear leather waste.  
(f) Equilibrium temperature (°C) to footwear leather waste.

Figure 4. Cold gas efficiency (%) and equilibrium temperature (°C) to industrial residues for a range of operational condition (air and steam demand).

For all cases presented, the figures show maximum equilibrium temperatures at $\phi = 1$ and $stm = 0$. This temperature is known as adiabatic flame temperature. The addition of steam causes an increasing of efficiency by the formation of more $H_2$. This addition also decreases the adiabatic flame temperature as shown in $\phi = 1$. The region of $\phi = 1$ also illustrates the conversion of all useful gas (fuel gas) that corresponds to cold gas efficiency equal to zero. Failure to account for an ash fraction in the proposed model would have great effect on the simulated values, especially for coal that has high ash content (56.2%). This would allow evaluating the effects of co-gasification of higher ash fuels (coal) together with lower ash fuels (biomass).

4. CONCLUSIONS

This study presents a general analysis of gasification of biomass and high ash coal through a thermodynamic equilibrium model. Predictions evaluate the process performance against operational conditions. The preliminary results show the range of 70 to 80% efficiency by using only air as gasifying agent with up to 65% of stoichiometric air demand. On the other hand, using air and steam those values can reach 85% to close to 100% with smaller than 40% of stoichiometric air demand. Next steps for this study include the model validation by literature data and the
evaluation of gasification of coal-biomass blends. At last, a complete evaluation of the best co-gasification conditions will be available to blends processing.

ACKNOWLEDGMENT

The study received financial support from the Brazilian Research Foundation (CNPq) under project 551386/2010-0 and also from the Brazil Coal National Network (http://www.ufrgs.br/rede_carvao).

REFERENCES


