A Simplified Model for Gasification of Oil Palm Empty Fruit Bunch Briquettes

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1.0 INTRODUCTION

The transition from fossil fuels to renewable energy sources is necessitated by global issues such as climate change and environmental sustainability. The gasification of biomass resources is considered a promising route for the production of clean energy fuels for the future [1-3]. Hence, the valorization of oil palm waste in Malaysia can significantly influence the sustainability of future clean energy supplies around the globe.

Currently palm waste is utilized for agricultural, pharmaceutical uses, however it can also be converted into densified fuels or briquettes with enhanced properties for thermochemical conversion. The use of oil palm empty fruit (EFB) briquettes for thermochemical applications has been explored [4-5]. However, research on the yield and composition of EFB briquette gasification is significantly lacking.

This study is aimed at investigating the effect of gasification temperature on the product gas yield and composition of EFB briquettes using a simplified stoichiometric equilibrium model. Similar models have been successfully adopted to investigate the thermochemical conversion of biomass species. Hence for a reacting system with known reaction mechanism, the model can be used to reasonably deduce the yield and composition of the gasification products.

Keywords: Stoichiometric; equilibrium; model; gasification; briquettes; temperature

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2.0 MODEL THEORY AND DEVELOPMENT

The model considers only the chemical reactions and species involved during gasification. Considering C, H and O gasification can be represented by the relation:

\[ CH_2O_{a}N_{c} + dH_2O + e(O_2 + 3.76N_2) \rightarrow n_1C + n_2H_2 + n_3CO + n_4H_2O + n_5CO_2 + n_6CH_4 + n_7N_2 \]  

(1)

Where \( n_1 \) to \( n_7 \) are stoichiometric coefficients; \( a, b, c \) are the mole ratios from the ultimate analysis; \( d \) and \( e \) are input parameters for steam and air respectively. The major reactions of gasification can be expressed as:

\[ C + CO_2 \rightarrow 2CO \]  

(2)
\[ C + H_2O \rightarrow CO + H_2 \]  

(3)
\[ C + 2H_2 \rightarrow CH_4 \]  

(4)
\[ CO + H_2O \rightarrow CO_2 + H_2 \]  

(5)

The atomic balance for C, H, and O can be represented by Equations 6-9 and the total number of moles in the gas phase is given by Equation 10.

\[ C: n_1 + n_3 + n_5 + n_6 = 1 \]  

(6)
\[ H: 2n_2 + 2n_4 + 4n_6 = a + 2d \]  

(7)

Graphical abstract
Considering the gasifier pressure, \( P \), the equilibrium constants for the reactions in Equations 2-4 can be represented by Equations 11-13:

\[
K_{e1} = \frac{\gamma_{CO}P}{\gamma_{CO}z}
\]  
(11)

\[
K_{e2} = \frac{\gamma_{CO}yHy_2^2P}{\gamma_{H_2}O}
\]  
(12)

\[
K_{e3} = \frac{\gamma_{CH_4}}{\gamma_{H_2}O}
\]  
(13)

\( K_{e1} \), \( K_{e2} \) and \( K_{e3} \) are the equilibrium constants for the Boudouard reaction, Water gas reaction and Methanation reactions respectively.

The mole fractions of the species CO, H\(_2\), H\(_2\)O and CO\(_2\) are represented by \( \gamma \) in the relation in Equation 14:

\[
\gamma_{CO} = \frac{n_{CO}}{n_{g}}; \quad \gamma_{CO2} = \frac{n_{CO2}}{n_{g}}; \quad \gamma_{H2} = \frac{n_{H2}}{n_{g}}; \quad \gamma_{H2O} = \frac{n_{H2O}}{n_{g}}; \quad \gamma_{CH4} = \frac{n_{CH4}}{n_{g}}
\]  
(14)

Substituting Equation 14 into Equations 11-13, and combining with Equations 6-10 gives the set of non-linear equations in 15-22.

\[
f_1 = n_1 + n_3 + n_5 + n_6 - 1
\]  
(15)

### Table 1 Standard heat of formation, empirical coefficients for Equation 24 [8]

<table>
<thead>
<tr>
<th>Product</th>
<th>( \Delta h_{\text{f,ref}} )</th>
<th>( a' )</th>
<th>( b' )</th>
<th>( c' )</th>
<th>( d' )</th>
<th>( e' )</th>
<th>( f' )</th>
<th>( g' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>-110.5</td>
<td>5.619</td>
<td>1.9\times10(^{3})</td>
<td>6.383 \times10(^{2})</td>
<td>-1.846 \times10(^{12})</td>
<td>-4.891 \times10(^{7})</td>
<td>0.868</td>
<td>-6.131 \times10(^{2})</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>-393.5</td>
<td>-1.9\times10(^{4})</td>
<td>3.122 \times10(^{4})</td>
<td>-2.448 \times10(^{6})</td>
<td>6.946 \times10(^{11})</td>
<td>-4.891 \times10(^{5})</td>
<td>5.27</td>
<td>-0.1207</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>-74.8</td>
<td>-4.62 \times10(^{2})</td>
<td>1.13 \times10(^{4})</td>
<td>1.319 \times10(^{6})</td>
<td>-6.647 \times10(^{12})</td>
<td>-4.891 \times10(^{7})</td>
<td>14.11</td>
<td>0.2234</td>
</tr>
<tr>
<td>H(_2)O</td>
<td>-241.8</td>
<td>-8.95 \times10(^{5})</td>
<td>-3.672 \times10(^{6})</td>
<td>5.209 \times10(^{8})</td>
<td>-1.478 \times10(^{12})</td>
<td>0</td>
<td>2.868</td>
<td>-0.0172</td>
</tr>
</tbody>
</table>

### 3.0 RESULTS AND DISCUSSION

#### 3.1 Ultimate Analysis

The ultimate analysis of the EFB briquette is presented in Table 2. By substituting the values of C, H, O, N, S, moisture content (steam) and equivalence ratio (ER) into the model, the yield and composition of EFB briquette gasification can be deduced.

<table>
<thead>
<tr>
<th>Carbon</th>
<th>Hydrogen</th>
<th>Nitrogen</th>
<th>Sulphur</th>
<th>Oxygen</th>
</tr>
</thead>
<tbody>
<tr>
<td>43.15</td>
<td>5.73</td>
<td>1.2</td>
<td>0.04</td>
<td>49.88</td>
</tr>
</tbody>
</table>

For gasification, the ER is between 0.2 and 0.3 [6]. However Mohammed et al., [3] deduced the optimal ER of 0.25 for EFB gasification which is in agreement with Basu [6]. Hence ER = 0.25 was chosen for the simulations in this study.

#### 3.2 Effect of Temperature on Producer Gas Composition

Temperature largely influences the product gas yield and composition of biomass gasification. In this study, the effect of temperature on product gas composition on EFB briquette gasification was investigated from 600 to 800°C and ER=0.25. The yield and product gas composition is presented in Figure 1.

As can be observed in Figure 1, the H\(_2\) and CO content increased while the CO\(_2\), N\(_2\) and CH\(_4\) content decreased with
increasing temperature from 600 to 800°C. Furthermore, the increase in H₂ and CO content is due to the effect of increasing temperature on the endothermic reactions in Equations 2 and 3. The H₂ content increased from 24.19 mol % to 25.54 mol % with increasing temperature, with peak production of 25.55 mol % at 750°C. However, the most significant changes in product gas content was observed for CO (14.08 to 40.51 mol %) and CO₂ (18.12 to 2.06 mol %).

3.3 Effect of Temperature on Gasifier Performance

The parameters heating value (HHV), cold gas efficiency (CGE) and carbon conversion efficiency (CCE) serve as a measure of the efficiency of gasification and the gasifier performance. Mathematically the HHV, CGE and CCE can be calculated from Equations 25-27.

The heating value (HHV) of the producer gas is given by the relation;

\[ HHV = [(H_2\% \times 30.52) + (CO\% \times 30.18) + (CH_4\% \times 95)] \times 4.1868 (\frac{MJ}{Nm^3}) \]  

The cold gas efficiency (CGE) is given by the relation;

\[ CGE = \frac{\alpha}{\mu} \times 100 \% \]  

Where \( \alpha \) represents the heating value of the producer gas; \( \mu \) is the heating value of the EFB briquettes. The carbon conversion efficiency (CCE) is given by the relation;

\[ CCE = \frac{\gamma}{\delta} \times 100 \% \]  

Where \( \gamma \), represents the carbon content in CO, CO₂ and CH₄; while \( \delta \) is the carbon content in EFB briquette.

The effect of temperature on the heating value (HHV), cold gas efficiency (CGE) and carbon conversion efficiency (CCE) is presented in Table 3.

Table 3: Effect of temperature on gasifier performance

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Higher Heating Val (MJ/Nm³)</th>
<th>Cold Gas Eff. (%)</th>
<th>Carbon Conv. Eff. (CCE, %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>4.87</td>
<td>27.72</td>
<td>25.43</td>
</tr>
<tr>
<td>650</td>
<td>6.04</td>
<td>34.39</td>
<td>30.52</td>
</tr>
<tr>
<td>700</td>
<td>7.13</td>
<td>40.59</td>
<td>35.56</td>
</tr>
<tr>
<td>750</td>
<td>7.93</td>
<td>45.11</td>
<td>39.35</td>
</tr>
<tr>
<td>800</td>
<td>8.38</td>
<td>47.71</td>
<td>41.54</td>
</tr>
</tbody>
</table>

The results indicate that the HHV, CGE and CCE increase with increasing temperature during gasification. This indicates the higher temperatures increase the overall efficiency of EFB briquette gasification. This can be attributed to the effect of higher temperatures on the thermal decomposition of the feedstock. The HHV values of EFB briquette gasification increased from 4 MJ/Nm³ to 8 MJ/Nm³ which is in good agreement for air gasification of biomass species [6]. Similar results have been reported in literature for biomass species [2-3].

In addition the results indicate that increasing gasification temperature by 30% from 600°C to 800°C results in ~ 72% and 63% increase in cold gas efficiency (CGE) and carbon conversion efficiency (CCE) respectively. We can conclude that gasification temperature has a greater effect on CGE than CCE, hence future studies can optimize EFB gasification by focusing on other parameters such as ER, pressure and heating rate.

4.0 CONCLUSION

The effect of gasification temperature on the product gas yield and composition of EFB briquettes was examined in this study. The results higher temperatures significantly influence the yield of the product gases H₂ and CO. In addition, we observed that gasification and gasifier performance is improved by increasing temperature. Furthermore, higher temperature increased cold gas efficiency (CGE) by a factor of 3 and carbon conversion efficiency (CCE) by a factor of 2. Hence we can conclude that the stoichiometric equilibrium model is robust, flexible and can be effectively used to predict the product gas yield and composition of EFB briquette gasification.

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