Research Article

Thermodynamic Model for Updraft Gasifier with External Recirculation of Pyrolysis Gas

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Most of the thermodynamic modeling of gasification for updraft gasifier uses one process of decomposition (decomposition of fuel). In the present study, a thermodynamic model which uses two processes of decomposition (decomposition of fuel and char) is used. The model is implemented in modification of updraft gasifier with external recirculation of pyrolysis gas to the combustion zone and the gas flowing out from the side stream (reduction zone) in the updraft gasifier. The goal of the model obtains the influences of amount of recirculation pyrolysis gas fraction to combustion zone on combustible gas and tar. The significant results of modification updraft are that the increases amount of recirculation of pyrolysis gas will increase the composition of H2 and reduce the composition of tar; then the composition of CO and CH4 is dependent on equivalence ratio. The results of the model for combustible gas composition are compared with previous study.

1. Introduction

The types commonly used in gasification are the fixed bed (updraft and downdraft) and fluidized bed. The updraft gasifier has many advantages but, on the other hand, produced high level of tar [1]. Several modifications to gasifier with recirculation of pyrolysis gas have been conducted to reduce the tar [2–4]. In previous study, we have modified type of updraft gasifier with pyrolysis gas recirculated externally to the combustion zone. Furthermore, the produced gas exits at the reduction zone (side stream) to reduce the tar [4].

Modeling is needed in the gasification process as a tool to predict the results that will be obtained from an experiment. Some thermodynamic modeling using Aspen Plus has been done before on updraft gasifier. Chen et al. conducted a model using one process of decomposition of MSW as fuel to see the effect of flue gases of combustion on the LHV; the results showed the flue gas will increase the LHV [5]. He et al. applied a model on Lurgi gasification process using one process of decomposition of coal as fuel to see the effect of oxygen/coal ratio on exergetic efficiency of the process; the results of modeling showed oxygen/coal ratio affecting exergetic efficiency of the process [6]. Modeling generally only uses one process of decomposition using ultimate analysis of fuel. In this study, we use a model using two processes of decomposition (decomposition of fuel and char) using the ultimate analysis of fuel and char. The model is implemented on updraft gasifier with external recirculation of pyrolysis gas [4].

Modeling aims to get the effect of the amount of external recirculations of pyrolysis gas flow to the combustion zone on the composition of the combustible gas (CO, H2, and CH4) and tar composition (C7H8O, C10H8).

2. Methodology

The process that occurs during the gasification includes drying, pyrolysis, reduction, and combustion; meanwhile each stage of the process results in a product for the next stage or directly results in a gasification process product. The processes of drying and pyrolysis are the processes that are not in an equilibrium state and may take place
instantaneously [7]. The composition of the product in its process is calculated using the mass and energy balance principles. The process of gasification and combustion is a process that can take place in a thermodynamic equilibrium state [8]. The composition of the product in thermodynamic equilibrium conditions can be calculated using Gibbs free energy minimization [9].

The reactions of combustion and gasification taking place at equilibrium conditions are as follows:

Boudouard reaction \( C + CO_2 \rightarrow 2CO \) (1)

Water gas reaction \( C + H_2O \rightarrow CO + H_2 \) (2)

Water gas shift reaction \( CO + H_2O \rightarrow CO_2 + H_2 \) (3)

Methanation reaction \( C + 2H_2 \rightarrow CH_4 \) (4)

Steam reforming reaction \( CH_4 + H_2O \)
   \( \rightarrow CO + 3H_2 \) (5)

Partial oxidation reaction \( C + \frac{1}{2}O_2 \rightarrow CO \) (6)

Oxidation reaction \( C + O_2 \rightarrow CO_2 \) (7)

In this simulation process, tar is modeled as cresol and naphthalene. Cresol is to represent nearly approaching heavy tar and naphthalene to represent light tar [10]. Tar will experience reforming when entering the combustion and gasification zones to form \( H_2 \) and \( CO \) through the reaction of steam reforming and dry reforming [11]:

\[ C_{n}H_{y}O_{z} + H_2O \rightarrow CO + H_2 + tar \] (8)

\[ C_{n}H_{y}O_{z} + CO_2 \rightarrow CO + H_2O + tar \] (9)

In equilibrium, the total Gibbs free energy \( (G_{total}) \) of the system is in a minimum state. The concentration of each compound \( (n_i) \) is obtained by minimizing the objective function \( G_{total} \):

\[ G_{total} = \sum_{i=1}^{N} n_i \Delta G_{f,i}^{0} + \sum_{i=1}^{N} n_i RT \ln \left( \frac{n_i}{\sum n_i} \right). \] (10)

Limits for completion of the objective function are expressed in the mass balance of elements:

\[ \sum_{i=1}^{N} a_{ij}n_i = A_j, \quad j = 1, 2, 3, \ldots, k. \] (11)

\( G_{total} \) is total Gibbs free energy, \( \Delta G_{f,i}^{0} \) is standard Gibbs free energy, \( R \) is universal gas constant, \( T \) is temperature, \( N \) is number of compounds, \( a_{ij} \) is number of atoms in element number \( j \) in mole of compound number \( i \), and \( A_j \) is number of atoms in element number \( j \) in mixture of reaction.

The Gibbs minimization equation can be solved using Langrange multiplier:

\[ L = G_{total} - \sum_{j=1}^{K} \lambda_j \left( \sum_{i=1}^{N} a_{ij}n_i - A_j \right), \] (12)

where \( \lambda \) is Langrange multiplier.

**Figure 1:** Updraft gasifier with external recirculation of pyrolysis gas [4].

Equilibrium conditions will be obtained if the partial derivative of the Langrange function is zero:

\[ \frac{\partial L}{\partial n_i} = \frac{\Delta G_{f,i}^{0}}{RT} + \sum_{i=1}^{N} \ln \left( \frac{n_i}{\sum n_i} \right) \]

\[ + \frac{1}{RT} \sum_{j=1}^{K} \lambda_j \left( \sum_{i=1}^{N} a_{ij}n_i \right) = 0. \] (13)

Calorific value of gas resulting from the gasification process is calculated based on

\[ LHV (kJ/Nm^3) = \gamma_{CO} \cdot 12621 + \gamma_{H_2} \cdot 10779 + \gamma_{CH_4} \cdot 35874. \] (14)

Modeling starts with the approach to the process of experiments that have been carried out by Surjosatyo et al. [4] as shown in Figure 1. Furthermore, the approaches are used to facilitate the simulation process. The approach is taken to the gas flows out from the gasifier at the end of the pyrolysis process, so that, in modeling, the fraction of the pyrolysis gas uncirculated does not enter the equilibrium zone and directly goes out of the reactor (Figure 2). Primary air and secondary air in the experiment are the total quantity of air for the combustion process, so that, in modeling, the total quantity of air only is used to enter the equilibrium zone.

Modeling is developed by applying the mass and energy balance as well as the Gibbs free energy minimization in the configuration of the updraft gasifier reactor with an external recirculation of pyrolysis gas as described in Figure 1. The mass and energy balance are used in the stages of drying, pyrolysis, reduction, and combustion processes. Gibbs free energy minimization is used during the combustion and
Table 1: Proximate and ultimate analysis of fuel.

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Value</th>
<th>Normalization</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proximate analysis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>Mass fraction (%)</td>
<td>10.24</td>
<td></td>
</tr>
<tr>
<td>Ash</td>
<td>Mass fraction (%)</td>
<td>2.71</td>
<td></td>
</tr>
<tr>
<td>Volatile</td>
<td>Mass fraction (%)</td>
<td>71.80</td>
<td></td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>Mass fraction (%)</td>
<td>15.25</td>
<td></td>
</tr>
<tr>
<td><strong>Ultimate analysis (dry basis)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>Mass fraction (%)</td>
<td>43.33</td>
<td>48.27</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Mass fraction (%)</td>
<td>5.11</td>
<td>5.69</td>
</tr>
<tr>
<td>Oxygen</td>
<td>Mass fraction (%)</td>
<td>38.61</td>
<td>43.01</td>
</tr>
</tbody>
</table>

![Figure 2: Configuration model updraft gasifier with external recirculation of pyrolysis gas.](image)

**Table 2: Pyrolysis product (fuel decomposition).**

<table>
<thead>
<tr>
<th>Compound</th>
<th>Mass (kg)</th>
<th>Mass fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0.49</td>
<td>0.10</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>H₂O</td>
<td>1.79</td>
<td>0.36</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.51</td>
<td>0.10</td>
</tr>
<tr>
<td>C₇H₈O (tar)</td>
<td>0.76</td>
<td>0.15</td>
</tr>
<tr>
<td>C₁₀H₈ (tar)</td>
<td>0.36</td>
<td>0.07</td>
</tr>
<tr>
<td>Char</td>
<td>0.88</td>
<td>0.18</td>
</tr>
<tr>
<td>Ash</td>
<td>0.12</td>
<td>0.02</td>
</tr>
</tbody>
</table>

**Table 3: Pyrolysis product of wood [13, 14].**

<table>
<thead>
<tr>
<th>Spices</th>
<th>Mass fraction (%)</th>
<th>Mass fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>64.8</td>
<td>51</td>
</tr>
<tr>
<td>Pyrolysis water</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>Tar (organic compound)</td>
<td>20.0</td>
<td>15</td>
</tr>
<tr>
<td>Char</td>
<td>15.2</td>
<td>21</td>
</tr>
</tbody>
</table>

**3. Results and Discussions**

3.1. The Effect of the Fraction of Pyrolysis Gas Recirculation.

Figure 3 presents the results for simulating the effect of the fraction of pyrolysis gas recirculation to the combustion zone.


Table 4: Simulation parameters.

<table>
<thead>
<tr>
<th>Number</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stoichiometric combustion air (kg/h)</td>
<td>25.6</td>
</tr>
<tr>
<td>2</td>
<td>Fuel flow rate (kg/h)</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Equivalence ratio (ER)</td>
<td>0.2 - 0.4</td>
</tr>
<tr>
<td>4</td>
<td>Pyrolysis gas recirculation fraction</td>
<td>0 - 1</td>
</tr>
</tbody>
</table>

![Table 4: Simulation parameters.](image)

**Figure 3: Gasification product according to pyrolysis gas recirculation fraction and equivalence ratio.**

CH$_4$ concentration tends to increase by the increase in the fraction of pyrolysis gas recirculation flow until the equivalence ratio reaches 0.2 and then will decrease. This is because, in the equivalence ratio below 0.2, the methanation reaction takes place better as it is an exothermic reaction. The addition of pyrolysis gas will increase the amount of H$_2$ for the methanation reaction. CH$_4$ carried by the fraction of pyrolysis gas recirculation flow also contributes to the increase of CH$_4$. In the equivalence ratio above 0.2, the methanation reaction will decrease by the increase of heat released on combustion reaction. H$_2$ in the pyrolysis gas will react with H$_2$O to produce H$_2$ through steam reforming reaction.

The tar content in the producer gas decrease by the increase in fractions of pyrolysis gas recirculation flow to the combustion zone as presented in Figure 3. This is because the tar experiences decomposition through the reforming process into H$_2$ and CO as it receives heat resulting from combustion process.

The pyrolysis gas recirculation flow fractions of zero (0) and one (1) represent each of the updraft and downdraft operations. The difference in the operating condition leads to significant difference in composition of combustible gas and tar, especially the concentration of H$_2$. It shows the significance of the effect of H$_2$O (water vapor) and tar contents in the pyrolysis gas on H$_2$ concentration. Research by Ueki et al. [19] and Saravanakumar et al. [20] presents a direct comparison between the operation of the updraft and downdraft gasifier or crossdraft gasifier. The results show there is a large difference in concentration between H$_2$ and tar.

The simulation results show that the variation of pyrolysis gas recirculation fraction gives an influence on the composition of the combustible gas and tar. Therefore, its variables are very important to do the experiment until the fraction of the pyrolysis gas recirculation flow reaches maximum.

3.2. The Effect of Equivalence Ratio. In the condition where the recirculation flow fraction is maximum (pyrolysis gas recirculation fraction of 1) as shown in Figure 4, an increase in the equivalence ratio will increase the concentration of H$_2$ until equivalence ratio of 0.3 and CO until equivalence ratio of 0.4 and then it will decrease. This is because the process will move towards the stoichiometric combustion where more heat is released. The increase in heat causes the Boudouard and the water gas reactions to be better. However, under a certain condition, its reaction will decrease because of the decrease of char quantity to produce heat when it burns a lot by the addition of the air supply (an increase of equivalence ratio) [21]. An increase in the equivalence ratio reduces the concentration of CH$_4$. It is caused by a decrease in methanation reaction. Methanation reaction is a reaction that releases heat; therefore it will be dominantly in the lower equivalence ratio. The results of model have a similar tendency with model results reported by Doherty et al. [7], Puig-Arnavat et al. [21], and Reed and Das [22], especially for Reed and Das model in which H$_2$ seems to continuously decrease. This is because in this modeling there is a heat loss.
4. Conclusions

The simulation results show that an increase in the fraction of the pyrolysis gas recirculation flow will affect the composition of the combustible gas and tar.

The concentration of $H_2$ increases in each equivalence ratio constant. The concentration of CO decreases until the equivalence ratio reaches 0.3 and increases above that. The concentration of CH$_4$ increases until the equivalence ratio reaches 0.2 and decreases above that.

The composition of C$_2$H$_4$O (tar) and C$_4$H$_8$ (tar) decreases by the increase in the fraction of pyrolysis gas recirculation flow into the combustion zone.

The best operating condition exists when the amount of recirculated flow is maximum (pyrolysis gas recirculation flow fraction of 1) and the equivalence ratio is 0.38.

Modeling and experimental results show a tendency to approach the same value, especially composition of CO and $H_2$.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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