Chemistry of Wood Gasification

Overview

Our first prototype model will be gasifying biomass and it is important to understand how adaptiveARC technology processes this feedstock. Our first run will use wood chips, a typical biomass waste stream.

Wood gasification has been around for more than one hundred years and was used extensively during World War II when oil availability was prohibitively unpredictable. Since then the technology has advanced considerably though application has been limited. adaptiveARC’s Cool Plasma Gasification™ technology represents a significant advance in the scientific and commercial development of wood gasification and this report will outline the chemical processes that convert wood chips into syngas.

What is Gasification Again?

Gasification is a process that uses molecular dissociation to convert energy stored in any given feedstock into usable energy in the form of a synthetic gas (syngas).

Unlike pyrolysis, thermal degradation in the complete absence of oxygen, or incineration, complete oxidation with an excess of oxygen, gasification uses a small, regulated amount of oxygen so that partial oxidation can increase the thermal efficiency of the entire process. This means that we have to understand the chemistry of both pyrolysis and combustion in order to analyze the parts they both play in gasification.

Why does using limited combustion improve the efficiency of our process?

- Molecular dissociation (pyrolysis) is highly endothermic, i.e. these chemical reactions require a lot of energy (heat) to run to completion
- Combustion is highly exothermic, i.e. these chemical reactions produce a lot of energy (heat) as they run to completion
- We use the energy generated through partial combustion to power molecular dissociation (the process that converts our feedstock into syngas)

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What is Wood?

Wood is an organic compound. It is a complex molecular structure primarily built with carbon, hydrogen, and oxygen atoms. The basic chemistry of biomass (hence wood) can be approximated as:

- $\text{CH}_{1.4}\text{O}_{0.6}$

The ultimate goal of the gasification process is to convert these wood molecules into syngas (hydrogen and carbon monoxide).

Chemical Breakdown of Wood Gasification

![Diagram of the gasification process]

Figure 1: The Gasification Process

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Figure 1, Box 1: Pyrolysis

As wood chips reach the bottom of the drying column they begin to undergo pyrolysis. The thermal energy from the reactor begins to overwhelm the bonding strength of some of the compounds within the wood. The volatile particles are vaporized, the heavier hydrocarbon molecules are converted into a gas (oil, tar, etc.), moisture in the wood is vaporized, and char (activated carbon) forms.

Table 1 shows experimental data for the outcomes of wood pyrolysis by mass. Table 2 displays the experimental data for the chemical composition of the dry gas produced during wood pyrolysis.

Table 1: Pyrolysis products from wood (kg/kg fuel)

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Char</th>
<th>Dry gas</th>
<th>Tar</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>988</td>
<td>0.092</td>
<td>0.662</td>
<td>0.06</td>
<td>0.186</td>
</tr>
<tr>
<td>1088</td>
<td>0.057</td>
<td>0.758</td>
<td>0.06</td>
<td>0.125</td>
</tr>
<tr>
<td>1188</td>
<td>0.051</td>
<td>0.765</td>
<td>0.06</td>
<td>0.124</td>
</tr>
</tbody>
</table>

Table 2: Dry gas composition from pyrolysis of wood (%vol.)

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>H₂</th>
<th>CO</th>
<th>CH₄</th>
<th>CO₂</th>
<th>C₂⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>988</td>
<td>16</td>
<td>54.3</td>
<td>12.8</td>
<td>12.8</td>
<td>4.1</td>
</tr>
<tr>
<td>1088</td>
<td>21.2</td>
<td>50.5</td>
<td>13.2</td>
<td>11.4</td>
<td>3.7</td>
</tr>
<tr>
<td>1188</td>
<td>26.4</td>
<td>46.8</td>
<td>12</td>
<td>11.5</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Figure 1, Box 2: Combustion

As the feedstock enters the reactor some of the wood molecules undergo combustion with the limited oxygen present in the chamber. By monitoring the level of oxygen present we can control this reaction to create the appropriate thermodynamic environment. Figure 2 shows the chemical reaction.

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6. Ibid.
Remember the approximate chemistry of wood is:

- CH\textsubscript{1.4}O\textsubscript{0.6}\textsuperscript{8}

So it turns out that in the case of wood \( x = 1.43 \) and \( y = 0.66 \). If we solve for the equation we get \( z = 1.02 \). This means we need 1.02 molecules of oxygen to fully combust a wood molecule.\textsuperscript{9}

*But* we have to remember that gasification only uses *partial oxidation*. This means we do not want to combust *all* the wood molecules, just *some* of them. We do this by keeping the value of \( z \) below 1.02 (this way only some, not all, of the wood molecules can undergo the combustion reaction in figure 2). In wood gasification we keep the value of \( z \) *75% below* the 1.02 level needed for complete combustion.\textsuperscript{10}

**Figure 1, Boxes 3 and 4: Gasification and the Boudouard Reaction**

The heat generated through exothermic combustion helps to drive the endothermic gasification and Boudouard reactions. Table 3 displays the major chemical reactions of gasification and their thermodynamic data.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Name</th>
<th>( \Delta_{r}H^a ) [kJ/mol]</th>
<th>( K_P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(s)+CO\textsubscript{2} ( \leftrightarrow ) 2CO (1.1)</td>
<td>Boudouard equilibrium</td>
<td>+172.54</td>
<td>14.1</td>
</tr>
<tr>
<td>C(s)+2H\textsubscript{2} ( \leftrightarrow ) CH\textsubscript{4} (1.2)</td>
<td>Hydrogenating gasification equilibrium</td>
<td>-74.91</td>
<td>0.071</td>
</tr>
<tr>
<td>C(s)+H\textsubscript{2}O ( \leftrightarrow ) CO+H\textsubscript{2} (1.3)</td>
<td>Heterogeneous water-gas shift equilibrium</td>
<td>+131.38</td>
<td>7.5</td>
</tr>
<tr>
<td>CH\textsubscript{4}+H\textsubscript{2}O ( \leftrightarrow ) CO+3H\textsubscript{2} (1.4)</td>
<td>Methane decomposition</td>
<td>+206.28</td>
<td>159</td>
</tr>
</tbody>
</table>


\textsuperscript{10} Ibid.

The heterogeneous reactions (Table 3, 1.1, 1.2, 1.3) take place as the char reacts with the gasifying agents.

The homogeneous reactions (Table 3, 1.4, 1.5, 1.6, 1.7) take place simultaneously between elements in the gas itself.

**Figure 1, Box 5: Equilibrium**

The heterogeneous and homogeneous gasification reactions eventually proceed to equilibrium as the syngas circulates within the reactor.

One of the unique strengths of adaptiveARC’s technology is that we can regulate the rate of circulation of the syngas and its residence time within the reactor. We also have the ability to manipulate the amount of water in the system and the content of the media gas in the torches. What does this mean? It means that we can, at least to a certain extent, control the equilibrium composition values of the syngas coming out of the reactor. In this way we can fine tune our syngas to whatever our customers want or need be it ethanol, fuel cells, or electricity produced in concert with a diesel genset.

**Using Different Media Gases**

We can use either compressed air or pure oxygen to power the plasma torches (in the future we will also be able to use landfill gas or other off gases). Using different media gases affects both the chemical composition and the BTU value of syngas in the reactor.

When we gasify wood with compressed air we can expect these approximate values: 10-18% hydrogen, 22-30% carbon monoxide, 6-9% carbon dioxide, 45-50% nitrogen, 3-5% hydrocarbons, and an energy value of 1700 kcal/cubic meter (180 BTU/cubic foot). Some of these compounds will break down further through our unique recirculation process.  

When we gasify wood with pure oxygen we can expect these approximate values: 24-26% hydrogen, 40% carbon monoxide, 23-25% carbon dioxide, 10% hydrocarbons, and an energy value of 2900 kcal/cubic meter (350 BTU/cubic foot). Again, some of these

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compounds will break down further through our unique recirculation process.\textsuperscript{13}

\textsuperscript{13} James A. Kent, \textit{Kent and Riegel’s Handbook of Industrial Chemistry and Biotechnology} (New York: Springer 2006), page 1282.