Carbonization of Sugarcane Bagasse and Heat Transfer Property by Pyrolysis in Superheated Steam and Nitrogen Atmosphere

A. Muaz HAPIPI, Md. Azhar UDDIN, and Yoshiei KATO †
(Received September 11, 2017)

Sugarcane bagasse is one of the biomass wastes which have a high thermal value (HHV) when dried and can be converted into energy by physical, biological or thermochemical process. Carbonization behavior of sugarcane bagasse and heat transfer properties were studied with superheated steam and nitrogen gas. In the carbonization experiment, char yield, HHV and carbon losing rate of superheated steam showed the same trend as that of nitrogen heating at the treatment temperature between 491 and 702 K. It means that no special oxidation occurs in superheated steam carbonization and the pyrolysis by superheated steam was the same as nitrogen gas. In the heat transfer properties, temporal change in the sample temperature attained a good agreement between calculation and experiment for superheated steam and nitrogen gas. The sample temperature in superheated steam atmosphere reached the set carbonization temperature faster than that in the nitrogen atmosphere due to the superior heat transfer property of radiation in addition to heat convection. As described above, superheated steam carbonizes the sugarcane bagasse with no additional oxidation as well as nitrogen pyrolysis and has better heat transfer property than nitrogen heating, which leads to conclusion that superheated steam is one of the useful carbonization tools of biomass.

Key Words
Organic waste, Carbonization, Sugarcane bagasse, Superheated steam, Pyrolysis

1. Introduction

Recently, the utilization of biomass resources has gained many interest due to the depletion of fossil fuel. Biomass is also one of the organic wastes which are produced in agriculture and forestry 1). Biomass waste can be converted into biofuels which are renewable and environmentally friendly 2). Carbon, hydrogen, oxygen and nitrogen are the most common substances in biomass 3). Elemental analysis of dry wood results in carbon (=0.52 kg/kg), oxygen (=0.405 kg/kg), hydrogen (=0.063 kg/kg), and nitrogen (=0.004 kg/kg) 4). Meanwhile, proximate analysis of wood shows volatile matter (=80.0 wt%), fixed carbon (=19.4 wt%), and ash (=0.65 wt%) 5). Meanwhile, proximate analysis of wood shows volatile matter (=80.0 wt%), fixed carbon (=19.4 wt%), and ash (=0.65 wt%) 6). Physical, biological and thermochemical processes are normally used to convert biomass to energy 7). Grinding, drying, filtration, pressing, extraction, and briquetting are the example of physical process. Biological process includes anaerobic digestion and fermentation. Thermochemical
process can be divided into gasification, pyrolysis and combustion\textsuperscript{5,8}. Pyrolysis is a process which converts biomass into liquid (tar and other organics), solid (char, charcoal)\textsuperscript{6,10}, and gaseous products (H\textsubscript{2}, CO, CO\textsubscript{2}, CH\textsubscript{4}, C\textsubscript{2}H\textsubscript{4}, C\textsubscript{2}H\textsubscript{6}) by heating biomass in the absence of oxygen or very low oxygen level\textsuperscript{6}. There are three types of biomass pyrolysis depending on the operating conditions: slow pyrolysis or carbonization (550-950 K), intermediate pyrolysis (850-1250 K) and fast pyrolysis (1050-1300 K)\textsuperscript{11}. The main goal for slow pyrolysis or carbonization is charcoal with lower moisture content and higher energy content while the main goal for intermediate and fast pyrolysis are bio-oil\textsuperscript{4,11-17}. Pyrolysis products can be used as substitute charcoal or as industrial fuel\textsuperscript{1}. In biomass pyrolysis, product yield and quality can be influenced by many factors such as catalysts, contact time, feed pretreatment, feed material, heating rate, particle size, moisture content, pressure, reactor geometry, temperature, residence time, and reagents\textsuperscript{19}. A considerable amount of research has been conducted on the pyrolysis process using inert gas such as nitrogen. Less attention has been paid to the others pyrolysis atmospheres such as superheated steam.

Superheated steam is produced by heating saturated steam to the temperature higher than boiling point\textsuperscript{20-23}. Compared with hot air and inert gas at the same temperature, this superheated steam has very unique properties such as, 1) a higher heating rate due to radiative heating in addition to convective heating, and 2) higher specific enthalpy\textsuperscript{20,24-29}.

The main purpose of this research is to investigate the carbonization of sugarcane bagasse and heating property via superheated steam and nitrogen gas heating. Sugarcane bagasse was used as a material of the organic wastes in this research because of their high thermal value when dried\textsuperscript{30}. Sugarcane bagasse is the residual material derived from sugarcane after extracting cane juice. Bagasse is carbon-rich biomass and suitable for biochar production. One of the possible ways to obtain high thermal value sugarcane bagasse is to convert to biochar by carbonization process. Some researches have been devoted to the problems of sugarcane bagasse hydrolysis to obtain sugar and furfural\textsuperscript{31-32}, but less attention has been paid to the sugarcane bagasse carbonization using superheated steam. In this research, the temperature increasing behavior and carbonization of the sugarcane bagasse under superheated steam and nitrogen atmosphere has been investigated and the results of both methods were compared.

2. Experiment

2.1 Method

Carbonization of the bagasse were conducted using the superheated steam device (Daiichi High Frequency Co. Ltd., Hi-HEATER 2005S) as shown in Fig. 1. The equipment consists of a boiler, a superheated steam generator, and a reaction chamber. Steam was produced from the boiler and then the temperature was risen to the setting temperature using superheated steam generator. Two thermocouples (A, B) were attached to the reaction chamber (A) and sample (B) to measure chamber temperature $T_{shs}$ [K] and sample temperature $T_{m}$ [K].

First, superheated steam temperature in the chamber was set to the desired chamber temperature (491, 541, 579, 617, 650, and 702 K). When the chamber temperature became almost constant, 5 g of the dried pellet as described in the section 2.3 was inserted in a sample basket, and placed in the chamber. Carbonization was carried out for 5, 10, 15, 20, 25 and 30 min at all temperatures. The flow rate of superheated steam in the reaction chamber was fixed to 10 kg/h. After the carbonization finished, sample was cooled down below 343 K. Then, the sample was dried at 383 K for 24 h to remove condensed water trapped in the carbonized residue.

On the other hand, carbonization via nitrogen gas was carried out by using the electric furnace (As One Co. Ltd., TMF-500N) shown in Fig. 2. The reaction tube and sample temperatures were measured by two thermocouples (A, B) attached on the outer wall of the reaction tube (A)
and sample (B), respectively. The reaction tube temperature, \( T_{N2} \) [K], was set to be equal to \( T_{shs} \) [K] for superheated steam such as 491, 541, 579, 617, 650 and 702 K. The effect of carbonization time for nitrogen heating was studied at \( T_{N2} = 617 \) K (\( T_m = 592 \) K) for 5-30 min. Nitrogen flow rate in the reaction chamber was fixed to 6.0 kg/h. Sample preparation and experimental setting is the same as superheated steam carbonization.

The relationship between the chamber (superheated steam) or reaction tube (nitrogen gas) and sample temperatures at 30 min is shown in Table 1. The sample temperature, \( T_m \) [K], in the reaction tube of Fig. 2 became finally lower than that of superheated steam in Fig. 1.

### Table 1 Chamber or reaction tube and sample temperatures for superheated steam and nitrogen heating practices at 30 min

<table>
<thead>
<tr>
<th>Superheated steam</th>
<th>Nitrogen gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber temperature, ( T_{shs} ) [K]</td>
<td>( T_{N2} ) [K]</td>
</tr>
<tr>
<td>491</td>
<td>490</td>
</tr>
<tr>
<td>541</td>
<td>539</td>
</tr>
<tr>
<td>579</td>
<td>576</td>
</tr>
<tr>
<td>617</td>
<td>616</td>
</tr>
<tr>
<td>650</td>
<td>647</td>
</tr>
<tr>
<td>702</td>
<td>701</td>
</tr>
</tbody>
</table>

#### 2.2 Characterization of bagasse

The remaining of the sample after carbonization was measured for the char yield. The char yield was calculated using the following equation:

\[
\text{Char yield [kg/kg]} = \frac{\text{Sample residue weight after carbonization [kg]}}{\text{Solid weight before carbonization [kg]}}
\]

(1)

Ultimate analysis of the sample was done before and after carbonization. Carbon, \( C \) [kg/kg], hydrogen, \( H \) [kg/kg], nitrogen, \( N \) [kg/kg] and sulfur, \( S \) [kg/kg] contents were analyzed by CHNS analyzer (Perkin Elmer series, 2004 II) for the ultimate analysis. While oxygen, \( O \) [kg/kg] content was calculated from the equation below:

\[
O = 1 - (C + H + N + S)
\]

(2)

Higher heating value, \( HHV \) [J/kg], of the sample can be calculated with ultimate analysis data and the equations can be obtained as follows:

\[
HHV = (34.308 \text{ MJ/kg} \times C + (42.492 \text{ MJ/kg} \times H)
+ (26.198 \text{ MJ/kg} \times N) + (2.776 \text{ MJ/kg} \times O)
\]

(3)

Carbon losing rate was calculated using the following equation:

\[
\text{Carbon losing rate [kg/kg]} = \frac{W_{\text{INIT,CINIT}} - W_{\text{FIN,CFIN}}}{W_{\text{INIT,CINIT}}}
\]

(4)

where \( W_{\text{INIT}} \) and \( C_{\text{INIT}} \) are the initial weight [kg] and carbon content [kg/kg] of sugarcane bagasse, respectively, while \( W_{\text{FIN}} \) and \( C_{\text{FIN}} \) are the weight [kg] and carbon content [kg/kg] of the sample after carbonization, respectively.

#### 2.3 Sample preparation

Sugarcane bagasse from Okinawa, Japan, was selected as a raw material in this study. Tables 2 and 3 show the ultimate and proximate analyses, respectively. Carbon, hydrogen, nitrogen and oxygen were recognized from the ultimate analysis. The fixed carbon was found to be 0.204 kg/kg and \( HHV \) was calculated from Eq. (3) as shown in Table 3. In order to make it easy to put it in the sample basket, the sample was pelletized. After grinded in a mixer, the resulting pulverized bagasse was dried in a dryer at temperature of 383 K for 24 h to remove the moisture content from the sample. It was compressed using a hydraulic presser to obtain the pellet form of the bagasse. The pellets were also dried in a dryer at temperature of 383 K for 24 h prior to the experiment. Photographic image of the pellet used for the experiment is shown in Fig. 3.

### 3. Results and discussion

#### 3.1 Carbonization experiment

##### 3.1.1 Char yield

Fig. 4 shows the effect of carbonization time on the char yield in superheated steam and nitrogen gas. Both char yields for superheated steam and nitrogen gas atmospheres decreased at the first 10 to 15 min and became constant within 25-30 min of carbonization.

The relationship between the char yield and carbonization temperature at carbonization time of 30 min is shown in Fig. 5. The char yield decreased with the increasing temperature and there was no different tendency between superheated steam and nitrogen gas. This suggests...
that the oxidation rate of carbon by superheated steam is very small and negligible.

3.1.2 Elemental analysis

Table 4 presents an example of temporal change in the sample composition at \( T_m = 616 \) K for superheated steam and 592 K for nitrogen gas practices, respectively. There was only a small difference in the char composition between both carbonization atmospheres at each carbonization time. The temperature rising in superheated steam was unstable at the first 10 minutes of carbonization which resulted in the increasing and decreasing in the carbon content. The sample temperature effect on the composition at 30 min of carbonization time is shown in Table 5. The increasing carbonization temperature indicated the increase in carbon contents and decrease in oxygen contents \(^{35}\), although the carbon content decreased and the oxygen content increased at the sample temperature of 701 K in superheated steam and 663 K in nitrogen gas. It might be due to secondary cracking of the char into gaseous products \(^{36}\). \(^{37}\).

Fig. 6 shows an example of TGA curve of sugarcane bagasse. TGA curve was measured under nitrogen atmosphere with flow rate of 200 ml/min and heating rate of 5 K/min. The decomposition starts with the evaporation of water (350 K) and followed by decomposition of hemicellulose (470-530 K), cellulose (510-620 K) and lignin (550-770 K). The carbonization via superheated steam and nitrogen gas also seems to proceed due to the thermal decomposition as shown in Fig. 6.

Table 4 An example of temporal change in sample composition for superheated steam and nitrogen heating practices

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>Superheated steam at ( T_m = 616 ) K [10^{-2} kg/kg]</th>
<th>Nitrogen gas at ( T_m = 592 ) K [10^{-2} kg/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>H</td>
<td>N</td>
</tr>
<tr>
<td>0</td>
<td>46.0</td>
<td>6.2</td>
</tr>
<tr>
<td>5</td>
<td>62.5</td>
<td>4.7</td>
</tr>
<tr>
<td>10</td>
<td>57.6</td>
<td>4.8</td>
</tr>
<tr>
<td>15</td>
<td>60.3</td>
<td>4.3</td>
</tr>
<tr>
<td>20</td>
<td>62.8</td>
<td>4.1</td>
</tr>
<tr>
<td>25</td>
<td>62.9</td>
<td>4.2</td>
</tr>
<tr>
<td>30</td>
<td>63.4</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Table 5 Sample temperature effect on composition at 30 min of carbonization time

<table>
<thead>
<tr>
<th>Sample temperature [K]</th>
<th>Superheated steam [10^{-2} kg/kg]</th>
<th>Nitrogen gas [10^{-2} kg/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>H</td>
<td>N</td>
</tr>
<tr>
<td>Raw material</td>
<td>46.0</td>
<td>6.2</td>
</tr>
<tr>
<td>490</td>
<td>47.3</td>
<td>6.2</td>
</tr>
<tr>
<td>539</td>
<td>50.1</td>
<td>6.0</td>
</tr>
<tr>
<td>576</td>
<td>54.5</td>
<td>5.7</td>
</tr>
<tr>
<td>616</td>
<td>63.4</td>
<td>4.4</td>
</tr>
<tr>
<td>647</td>
<td>64.1</td>
<td>4.0</td>
</tr>
<tr>
<td>701</td>
<td>60.8</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Fig. 4 Temporal change in char yield for superheated steam and nitrogen gas heating practices

Fig. 5 Relationship between char yield and sample temperature at 30 min of carbonization
3.1.3 Higher heating value (HHV)

The HHV for both atmospheres of superheated steam and nitrogen gas were calculated by Eq. (3) to evaluate the quality of char as a fuel. Fig. 7 shows the effect of carbonization temperature on the HHV. Carbon is the element that increases the heating value while oxygen is the element that suppresses the heating value of char. With the increase in carbonization temperature, the HHV was almost kept constant until about 500 K, increased until about 650 K and decreased slightly after that as shown in Fig. 7. The decrease in the HHV was due to the decreasing carbon content at this temperature as shown in Table 5. As described in the section 3.1.2, the secondary cracking of the char into gaseous products seems to have caused the decrease in carbon content above the temperature around 650 K.

3.1.4 Carbon losing rate

The effect of carbonization time on the carbon losing rate calculated by Eq. (4) is shown in Fig. 8. The results indicated that the carbon losing rate for both superheated steam and nitrogen have the same trend, that is, the carbon losing rate increased until 10 min and after that it was almost kept constant. Due to the difference of sample temperature between superheated steam and nitrogen, superheated steam practice had a higher carbon losing rate compared with nitrogen.

Fig. 9 shows the effect of carbonization temperature on the carbon losing rate for superheated steam and nitrogen practices at 30 min of carbonization. It suggests that the pyrolysis by superheated steam occurs without oxidation as well as the char yield in Fig. 5.
3.2 Heat transfer behavior of superheat steam and nitrogen gas heating

3.2.1 Calculation model

Heat transfer of superheated steam and nitrogen heating practices has been studied in this research. Superheated steam heats the material by convection, radiation and condensation heat transfers compared with hot air or nitrogen gas which only heats through convective heat transfer. Heat transfer properties of superheated steam can be calculated by using a heat balance equation as follows:

\[ hA(T_{ss} - T_s) + \varepsilon_{ss}A(\tau_{ss}^4 - \tau_s^4) + m_i(dW/dt)r_i = m_i(C_i + WC_w)(dT_s/dt) \]

where, \( h \) : heat transfer coefficient \([\text{W/(m}^2\cdot\text{K})]\), \( A \) : surface area of sample \([\text{m}^2]\), \( T_{ss} \) : steam temperature \([\text{K}]\), \( T_s \) : sample temperature \([\text{K}]\), \( \varepsilon_{ss} \) : emissivity of superheated steam and sample \([\text{]}\), \( \sigma \) : Stefan-Boltzmann constant \([\text{W/(m}^2\text{K}^4)]\), \( m_i \) : sample weight \([\text{kg}]\), \( r_i \) : latent heat of condensation \([\text{J/kg}]\), \( C_i \) : specific heat of sample \([\text{J/(kg·K)}]\), \( WC_w \) : water content in sample \([\text{J/kg-water/kg-sample}]\), \( C_w \) : specific heat of water \([\text{J/kg·K}])\).

The left side of Eq. (5) is convection, radiation and condensation heat transfers, respectively, and at the right side is the sensible heat of the sample. The following assumptions should be given to obtain the proper calculation.

1) There is no steam condensation during the carbonization because the experimental temperature is sufficiently high.
2) Each heat transfer coefficient of superheated steam and nitrogen heating is constant in the temperature range of this experiment.

According to the above assumption 1) and the initial water content, \( W_i = 0 \text{ kg-water/kg-sample} \), in this experimental condition, terms of the water condensation and the heat of evaporation can be neglected in Eq. (6), that is, \( dW/dt = W = 0 \).

The \( h \) value in Eq. (5) was changed until the calculated sample temperature matched with the experimental temperature. Using \( \varepsilon_{ss} \) described in the section 3.2.2, heat balance equation of Eq. (5) was solved by Runge-Kutta Fehlberg method.

3.2.2 Setting of emissivity, \( \varepsilon_{ss} \)

Emissivity between superheated steam and the sample were calculated by using the following equation:

\[ 1/\varepsilon_{ss} = 1/\varepsilon_i + A_i/A_s(1/\varepsilon_{ss}) \]

where, \( \varepsilon_i \) is biomass sample emissivity \([\text{]}\), \( \varepsilon_{ss} \) is superheated steam emissivity \([\text{]}\), \( A_i \) is surface area of the sample \([\text{m}^2]\), and \( A_s \) is the surface area of superheated steam \([\text{m}^2]\).

Emissivity of the sample used in this research was 0.90 which is the emissivity value of woody biomass. Effective gas thickness, \( LG \) \([\text{m}]\), of the superheated steam is required for the calculation of the emissivity, \( \varepsilon_{ss} \) of the superheated steam and can be calculated using the equation below:

\[ LG = 4 \times (\text{Volume of superheated steam / surface area of superheated steam}) \times 0.85 \]

Volume and surface area of superheated steam were calculated from the size of the reaction chamber used in this experiment (Fig. 1) and the effective gas thickness became 0.17 m. From the superheated steam radiation diagram and \( LG = 0.17 \text{ m} \), the value of superheated steam emissivity, \( \varepsilon_{ss} \), was 0.29 at 491 K, 0.28 at 541 K, 0.27 at 579 K, 0.26 at 617 K, 0.26 at 650 K and 0.24 at 663 K, respectively.

Finally, the emissivity between superheated steam and the sample was calculated and the result was 0.88 at all temperatures.

3.2.3 Comparison of sample temperature change between experiment and calculation

Fig. 10 shows the temporal change in sample temperature of the experiment and calculation for superheated steam practice. The sample temperature increased rapidly and became constant until 5 min. Most of the results showed a good agreement between the calculated and experimental temperature when \( h = 7 \text{ W/(m}^2\text{K}) \) was used. The temporal change in sample temperature of the experiment and calculation with no radiation, that is, \( \varepsilon_{ss} = 0 \) in Eq. (5) is shown in Fig. 11. The calculated curve increased more slowly than the experimental one. Thus, the radiation heat transfer by superheated steam played an important role in the pyrolysis of sugarcane bagasse.
Two kinds of the temporal change in sample temperature of the experiment and calculation for nitrogen gas using electric furnace is shown in Fig. 12. Here, the calculation model of nitrogen only consists of convective heat transfer because neither condensation nor radiation occurs during the carbonization with nitrogen gas. The experimental sample temperature was moderately increased and held constant between 10 and 15 min. A good agreement was achieved between the experiment and calculation when the value of \( h = 9 \text{ W/(m}^2\text{K)} \) in Eq. (5) was used. The difference of the \( h \) value between superheated steam and nitrogen is estimated to be due to the physical properties and the experimental conditions.

The correlation on heat convection of fluid parallel to flat plate is given by Eq. (8) \(^{(4)}\):

\[
\frac{Nu}{h} \propto \frac{Re^{1/2}}{Pr^{1/3}}
\]

\[
Nu \equiv hL/\lambda
\]

\[
Re \equiv \rho ud/\mu
\]

\[
Pr \equiv C_p \mu/\lambda
\]

Here, \( Nu \): Nusselt number [-], \( Re \): Reynolds number [-], \( Pr \): Prandtl number [-], \( L \): plate length [m], \( \lambda \): thermal conductivity [W/(m·K)], \( \rho \): fluid density [kg/m\(^3\)], \( u \): fluid velocity [m/s], \( d \): equivalent cross-sectional area diameter [m], \( \mu \): viscosity [Pa·s], \( C_p \): heat capacity at constant pressure [J/(K·kg)]. Substituting the average physical properties between 490 and 702 K and the experimental conditions into Eq. (8), the following equation is given.

\[
\frac{Nu_{\text{steam}}}{Nu_{\text{nitrogen}}} = \left( \frac{Re_{\text{steam}}}{Re_{\text{nitrogen}}} \right)^{1/2} \left( \frac{Pr_{\text{steam}}}{Pr_{\text{nitrogen}}} \right)^{1/3}
\]

\[
= (0.37/0.57)(0.23/1.48)(3.1 \times 10^{-3}/3.6 \times 10^{-3})^{1/2} \times
\]

\[
(2.0 \times 10^{3}/1.1 \times 10^{3})(3.1 \times 10^{-5}/3.6 \times 10^{-5})(4.6 \times 10^{-2}/4.4 \times 10^{-2})^{1/3}
\]

\[
= 0.80
\]

(12)

Here, the suffixes of steam and nitrogen mean superheated steam and nitrogen heating, respectively. Thus,

\[
\frac{h_{\text{steam}}}{h_{\text{nitrogen}}} = \left( \frac{\lambda_{\text{steam}}}{\lambda_{\text{nitrogen}}} \right) \left( \frac{Nu_{\text{steam}}}{Nu_{\text{nitrogen}}} \right)
\]

\[
= (4.6 \times 10^{-2}/4.4 \times 10^{-2})(0.80) = 0.84
\]

(13)

On the other hand, \( h_{\text{steam}}/h_{\text{nitrogen}} \) value of this experimental study is obtained from Figs. 10 and 12 as follows.

\[
\frac{h_{\text{steam}}}{h_{\text{nitrogen}}} = 7/9 = 0.78
\]

(14)

Considering that the average values of the physical properties and the experimental conditions were used for the calculation of Eq. (12), the experimental heat transfer coefficient was roughly explained by the correlation equation of heat transfer coefficient in Eq. (8).

Fig. 13 shows the predicted sample temperature change between superheated steam and nitrogen gas at the same carbonization temperature.
change of superheated steam and nitrogen gas when the final sample temperatures are 616 and 539 K, and the same h value of 5 W/(m² K). The temperature of superheated steam approached to the set temperature faster than that of nitrogen gas due to the addition of radiation heat transfer. In this situation, carbonization of biomass via superheated steam is preferable to heated nitrogen.

As large amount of heat is necessary to produce superheated steam compared to the same temperature of nitrogen, it is desirable to make use of the extra energy for superheated steam generation at works such as steelmaking plant etc.

In this study, the dry sugarcane bagasse was used to investigate the carbonization and heat transfer behavior. As the next step, the raw sugarcane bagasse with water content will be used to make clear the effect of water condensation and evaporation on the temperature change during pyrolysis in superheated steam.

4. Conclusions

The carbonization of the sugarcane bagasse and its heat transfer behavior during the pyrolysis in superheated steam and nitrogen atmospheres.

1) The char yield, elemental analysis, higher heat value, and carbon losing rate of superheated steam showed the same tendency as that of nitrogen heating at the treatment temperature between 491 and 702 K.

2) The same carbonization behavior of sugarcane bagasse during the pyrolysis between superheated steam and nitrogen gas suggests no additional oxidation by superheated steam.

3) The differences in the char yield, elemental analysis, higher heat value, and carbon losing rate between superheated steam and nitrogen in this experiment were due to the difference in the sample temperature.

4) A good agreement was achieved between the temporal change in sample temperature of the experiment and calculation for superheated steam and nitrogen gas heating practices.

5) The heat transfer of superheated steam was faster than that of nitrogen gas due to additional radiative heating.

References


40) Suzuki, K., Kanetsusuijouki no tokusei, Tokyo, NTS (2005)