Study on CO2 gasification reactivity and physical characteristics of biomass, petroleum coke and coal chars

Wei Huo, Zhijie Zhou *, Xueli Chen, Zhenghua Dai, Guangsuo Yu *

Key Laboratory of Coal Gasification and Energy Chemical Engineering of Ministry of Education, Shanghai Engineering Research Center of Coal Gasification, East China University of Science and Technology, Shanghai 200237, PR China

HIGHLIGHTS

- CO2 gasification kinetics with biomass, coke and coal chars were measured in TGA.
- Physical structures and chemical components of different chars were examined.
- The crystalline structure is an important factor to evaluate gasification reactivities of various chars.
- The difference in diffusion effects among gasification with various chars are obvious.

ABSTRACT

Gasification reactivities of six different carbonaceous material chars with CO2 were determined by a Thermogravimetric Analyzer (TGA). Gasification reactivities of biomass chars are higher than those of coke and coal chars. In addition, physical structures and chemical components of these chars were systematically tested. It is found that the crystalline structure is an important factor to evaluate gasification reactivities of different chars and the crystalline structures of biomass chars are less order than those of coke and coal chars. Moreover, initial gasification rates of these chars were measured at high temperatures and with relatively large particle sizes. The method of calculating the effectiveness factor \( \eta \) was used to quantify the effect of pore diffusion on gasification. The results show that differences in pore diffusion effects among gasification with various chars are prominent and can be attributed to different intrinsic gasification reactivities and physical characteristics of different chars.

1. Introduction

Gasification technology, as an efficient technology for solid fuel utilization, is used to convert carbonaceous materials including coal, biomass, petroleum coke, etc. into fuel gas or syngas. Entrained flow gasification, a leading and modern technology in the gasification field, has been widely used nowadays. This technology is commercially available on large-scale industry (mainly for fossil fuels), since its high efficiency. However, huge amount of CO2 is released during the process of fossil fuels gasification, which will lead to environmental pollution. Biomass, as renewable energy source, has a lower environmental effect than fossil fuels, because the contribution of CO2 to environmental pollution for biomass is considered to be nil (Zanzi et al., 1996). Therefore, the replacement of fossil fuels with biomass may be a good choice to limit the environmental pollution. But the status of biomass gasification technology is that there is much interest for gasification but hardly any commercially projects are implemented (Kirkels and Verbong, 2011). So in order to fully utilize bioresources in the field of gasification, it is necessary to study biomass gasification more detailed.

In general, the gasification process in the gasifier is very complex and includes water evaporation, volatiles pyrolysis, combustion, volatiles gasification and char gasification. Among these processes, char gasification is the controlling step because of its slower reaction rate (Dupont et al., 2011). In addition, the CO2 gasification rate of chars is much slower than the steam gasification rate of chars, so char-CO2 gasification rate is considered as the rate-determining step (Roberts and Harris, 2000). Therefore, a clear understanding of char-CO2 kinetics is important for design and stable operation of entrained flow gasifiers (Zou et al., 2007).

Char-CO2 gasification kinetics has been widely studied in the past years. However, for the chars of different carbonaceous materials (coal/petroleum coke or biomass), the CO2 gasification
reactivities are difficult to predict because of the difference in their physicochemical properties (Sawetaporn et al., 2010). Miura et al. (1989) found that the CO$_2$ gasification reactivity of the low rank coal char was significantly influenced by alkali and alkaline earth metals. Lahijani et al. (2013) draw the same conclusion in the field of biomass gasification. However, other researchers found that the pore volume and the surface area of the char have effect on gasification reactivity (Liu et al., 2006). Kim et al. (2011) thought that the influence extent of individual coal property on CO$_2$ gasification reactivity decreases in the order of alkali ratio, volatile content, mesopore volume, alkali index and specific surface area, but linear correlation coefficients between gasification reactivity and each parameter were all lower than 0.80. Although it is well known that the CO$_2$ gasification reactivity of biomass is higher than those of most fossil fuels, there is no acceptable factor for evaluating the gasification reactivities of different carbonaceous materials. Therefore, in order to evaluate the difference in gasification reactivities between biomass and coal or petroleum coke, an acceptable factor should be found or developed.

On the other hand, the gasification temperatures are high and the particle size distributions are wider under realistic entrained flow gasification conditions. For example, the gasification temperatures and the particle size distributions in Texaco and opposed multi-burner (OMB) coal/water slurry (CWS) entrained flow gasifiers are up to 1673 K and from dozens to hundreds micrometers, respectively. Thus, the knowledge of the gasification in these conditions is of great importance. In addition, the gasification reactivity obtained in these conditions will be influenced by pore diffusion. Although the effect of pore diffusion on gasification has been studied these years, for example, Mani et al. (2011) and Barea et al. (2006) quantified the diffusional phenomena during biomass char CO$_2$-gasification, Paviet et al. (2008) evaluated the effects of diffusional resistance on wood char gasification and Kajitani et al. (2006) measured char gasification rate in the present of pore diffusion, there is little reported literature which compared differences in pore diffusion effects among CO$_2$ gasification with various carbonaceous materials. In addition, gasification reactivities in conditions of high temperatures (>1273 K) and relatively large particle sizes (~250 μm) were measured in order to clarify differences in pore diffusion effects among CO$_2$ gasification with various carbonaceous materials.

2. Methods

2.1. Char preparation

Two different kinds of biomass, three coals of different ranks and a petroleum coke were used in this study. Two kinds of biomass are saw dust (SD) from a furniture factory in Shanghai and rice (RS) straw from surrounding area in Shanghai. Three coals are Neimeng lignite (NM), Shenfu bituminous coal (SF) and Zunyi anthracite (ZY). The petroleum coke (PC) is from Sinopec Shanghai Gaoqiao Company. These samples were devolatilized in a fixed bed reactor under a continuous nitrogen atmosphere at the temperature of 1123 K and heating rate of 25 K/min. Once the temperature was reached 1123 K, these samples were kept at the temperature for another 30 min to ensure complete pyrolysis. After devolatilization, the char samples were sieved and the particle sizes of <46, and ~250 μm were chosen as samples, respectively.

2.2. Property tests of samples

The proximate and ultimate analyses of raw materials and chars were conducted according to the Chinese standard GB/T 212-2001 and GB/T 476-2001, respectively. The results are shown in Table 1. The average particle size of each char sample was tested by Malvern Mastersizer 2000 laser particle size analyzer. The results are shown in Table 2. The ash constituents of char samples were tested by X-ray fluorescence spectrometer (XRF)

Carbon crystallite structures of chars were tested by XRD (Rigaku D/max-2550VB/PC, Japan). The chars were scanned in a step-scan mode (0.02/step) over the angular range of 10–80° using 100 mA and 40 kV Cu Kα radiation. The stacking heights ($L_c$) and the spacing between graphitic sheets ($d_{002}$) were calculated by the Bragg formula and Scherrer formula (Feng et al., 2003).

\[
d_{002} = \frac{\lambda}{2 \sin \theta}
\]
The specific surface area and the pore volume of each char were measured at the temperature of 77 K and the relative pressure range from 0.01 to 0.99. The specific surface area was calculated using BET method. The average particle size of each char sample, Table 1, was calculated by Micromeritics ASAP-2020M automated surface area and pore size distribution analyzer. Chars were degassed at the temperature of 1123 K, 1173 K, 1223 K and 1273 K in N2 at atmospheric pressure. When the desired temperature is reached, N2 is replaced by CO2 with the flow rate 80 mL/min. The final temperature is kept for gasification until no evident weight loss is observed. In addition, in order to evaluate the pore diffusion effect on char gasification, chars with the particle size of ~250 μm were gasified at higher gasification temperatures and a wider temperature range (1123–1573 K). The gasification process of chars with the particle size of ~250 μm is the same as that of very fine particles.

### 3. Results and discussion

#### 3.1. Char gasification reactivity

The carbon conversion (x) for gasification is expressed by following:

\[ x = \frac{W_0 - W_t}{W_0 - W_{\text{wash}}} \]

Gasification rate (r) is defined as differential of carbon conversion to gasification time (t):

\[ r = -\frac{1}{W_0 - W_{\text{wash}}} \frac{dx}{dt} = \frac{dw}{dt} \]

Since the particle size and the pore structure of the char are constantly changing during the gasification process, the gasification rate is not a constant. In order to evaluate reactivities of different chars quantitatively, the reactivity index \( R_{0.5} = (W_{0.5} / W_{50}) \) proposed by Takayuki et al. (1985) is used in this study. \( W_{50} \) is the time at the carbon conversion of 50%.

The reactivity index for each char with the particle size <46 μm is shown in Fig. 2. For each char, it is obvious that the reactivity index \( R_{0.5} \) increased with the gasification temperature. It means that the gasification reactivity is dramatically influenced by gasification temperature. Furthermore, the reactivity index of PC char, ZY char, SF char, NM char, RS char, SD char at temperatures of 1123–1273 K were 0.0005–0.0034 min⁻¹, 0.0021–0.019 min⁻¹, 0.0117–0.20 min⁻¹, 0.051–0.26 min⁻¹, 0.053–0.040 min⁻¹ and 0.034–0.54 min⁻¹, respectively. Although Gasification reactivities of two biomass chars were just slightly higher than that of NM char, they were much higher than those of coke or high temperature. Furthermore, the reactivity index of PC char, ZY char, SF char, NM char, RS char, SD char at temperatures of 1123–1273 K were 0.0005–0.0034 min⁻¹, 0.0021–0.019 min⁻¹, 0.0117–0.20 min⁻¹, 0.051–0.26 min⁻¹, 0.053–0.040 min⁻¹ and 0.034–0.54 min⁻¹, respectively. Although Gasification reactivities of two biomass chars were just slightly higher than that of NM char, they were much higher than those of coke or high gasification temperature. It means that gasification reactivity of RS char was similar with that of NM char, they were much higher than those of coke or high
rank coal chars. This trend is in accordance with the results obtained by other researchers (Zhu et al., 2008; Li et al., 2013). The detailed order of gasification reactivity sequence for various chars can be ranked as PC char < ZY char < SF char < NM char < RS char < SD char.

3.2. Correlation between gasification reactivity and structure of char

Previous extensive investigations (Kassaoka et al., 1987; Lahi-jani et al., 2013; Hattingh et al., 2011) have studied the correlation between the gasification reactivity and characteristics of the raw material including volatile matter, mineral, carbon content and so on. In addition, the structure of the char may also affect the gasification reactivity. However, volatile matter in this study may not be the main factor which affects the gasification reactivity, since chars obtained in this study have experienced a comparatively complete pyrolysis and most of the volatile matter content (almost > 75%) has been removed. As shown in Table 1, the main content of the chars is fixed carbon and ash. In order to denote the effects of minerals in ash on char gasification, the alkali index was proposed by research (Mitsuhiro et al., 1982). The alkali index (A value) is calculated by the equation:

\[ A = \text{Ash} \times \frac{\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO} + \text{Na}_2\text{O} + \text{K}_2\text{O}}{\text{SiO}_2 + \text{Al}_2\text{O}_3} \]  

(5)

As shown in Table 3, the order of the alkali index sequence for various chars can be ranked as PC char < NM char < SD char < RS char < SF char < ZY char. There was no good relationship between the reactivity and alkali index for different chars. Based on these results and reasons, it could be concluded that the characteristics of the raw material was not the main factor which affect the gasification reactivity. Thus, the structure or the carbon crystalline structure of the char may play a significant role in char gasification reactivity.

On the whole, the char with larger BET specific surface area (\(S_{\text{BET}}\)) possesses higher gasification reactivity (Malekshahian and Hill, 2011). Fig. 3 shows the \(S_{\text{BET}}\) of each char. The order of \(S_{\text{BET}}\) sequence for various chars can be ranked as PC char < ZY char < SF char < NM char < SD char < RS char. This phenomenon indicates that the relationship between gasification reactivity and \(S_{\text{BET}}\) has the same tendency (except SD char). Miura et al. also stated that the gasification reactivity of low-rank coal chars is not controlled by the pore structure. Moreover, some studies (Zhang et al., 2010) indicated that the pore structure obtained by the method of physical adsorption was not a clear descriptor in predicting the gasification reactivity of different coal rank chars. Although the \(S_{\text{BET}}\) performs better than the alkali index on the alkali index, it even cannot well explain the difference in reactivity among different chars.

Based on the results mentioned above, a suitable factor or parameter should be found to evaluate the gasification reactivity of different chars. Compared to the XRD spectra of two biomass chars, chars obtained from coals or coke showed a relative narrower pattern of diffraction peak respectively. Especially to PC char, it showed smooth and sharp pattern of the \((002)\) peak of graphite. This implies that PC char and three coal chars may possess more order crystalline structures than biomass chars. The carbon crystalline structure can be reflected quantitatively by the stacking heights (\(L_c\)) and the spacing between graphitic sheets (\(d_{002}\)). These two parameters were calculated using Eqs. (1) and (2). The results are shown in Table 4. \(L_c\) values of two biomass chars were much smaller than that of the other four chars, while \(d_{002}\) values of two biomass chars were much larger than that of the other four chars. In general, the larger the \(L_c\) value is (and the smaller the \(d_{002}\) values is), the more order the crystalline structure is created. The order of the \(L_c\) value sequence for various chars can be ranked as PC char > ZY char > SF char > NM char > RS char > SD char. This trend was opposite to the trend of the gasification reac-

![Fig. 2. The reactivity index for each char with the particle size <46 μm.](image1)

![Fig. 3. The \(S_{\text{BET}}\) of each char.](image2)

<table>
<thead>
<tr>
<th>Raw material</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>MgO</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saw dust</td>
<td>13.21</td>
<td>3.50</td>
<td>1.48</td>
<td>37.18</td>
<td>3.72</td>
<td>6.75</td>
<td>8.20</td>
<td>3.4</td>
</tr>
<tr>
<td>Rice straw</td>
<td>61.33</td>
<td>0.25</td>
<td>3.29</td>
<td>5.04</td>
<td>0.32</td>
<td>0.59</td>
<td>2.77</td>
<td>5.0</td>
</tr>
<tr>
<td>Neimeng</td>
<td>39.76</td>
<td>12.08</td>
<td>3.29</td>
<td>5.04</td>
<td>0.32</td>
<td>0.59</td>
<td>2.77</td>
<td>3.3</td>
</tr>
<tr>
<td>Shenyi</td>
<td>25.29</td>
<td>11.26</td>
<td>12.89</td>
<td>34.62</td>
<td>1.60</td>
<td>0.71</td>
<td>1.39</td>
<td>8.8</td>
</tr>
<tr>
<td>Zunyi</td>
<td>43.05</td>
<td>20.78</td>
<td>21.43</td>
<td>7.42</td>
<td>0.86</td>
<td>2.90</td>
<td>9.8</td>
<td></td>
</tr>
<tr>
<td>Petroleum coke</td>
<td>15.08</td>
<td>3.31</td>
<td>1.74</td>
<td>31.51</td>
<td>0.40</td>
<td>0.33</td>
<td>1.79</td>
<td>0.3</td>
</tr>
</tbody>
</table>

| Chars       | \(d_{002}\) | \(L_c\) | \(L_c/d_{002}\) |
|-------------|-------------|--------|----------------|---|
| SD char     | 0.6932      | 0.3679 | 1.88           |
| RS char     | 0.7324      | 0.3821 | 1.92           |
| NM char     | 0.3579      | 0.7948 | 2.22           |
| SF char     | 0.3705      | 0.8833 | 2.38           |
| ZY char     | 0.3396      | 1.1820 | 3.48           |
| PC char     | 0.3544      | 1.4646 | 4.13           |
productivity. This means the char with lower value of $L_c$ possesses higher gasification reactivity. However, the trend of $d_{0.02}$ values for different chars is not the same as that of the gasification reactivity. Hence, in order to consider these two parameters comprehensively, the $L_c$/$d_{0.02}$ was used. The results show that the $L_c$/$d_{0.02}$ value of the PC char was the largest and reached by 4.13, while $L_c$/$d_{0.02}$ values of two biomass chars were much smaller than that of the other four chars and reached by about 1.90. In addition, for three coal chars, the $L_c$/$d_{0.02}$ value increased with the coal rank. Hence, it can be concluded that the relationship between gasification reactivity and the $L_c$/$d_{0.02}$ value has the completely opposite tendency. This means that the char with more order crystalline structure possesses lower gasification reactivity. Therefore, the $L_c$/$d_{0.02}$ value can be developed to evaluate gasification reactivities of different chars.

The O/C and H/C mole ratios of six chars are presented in Table 1. It can be seen that the O/C and H/C mole ratios of two biomass chars were higher than that of the other four chars. The O/C and H/C mole ratios of PC char was the lowest among these six tested samples. It is well known that a relatively low O/C and H/C mole ratios of the sample were witness to a more graphitic structure. Therefore, it can be inferred that the structure of PC char is the most graphitic and the detailed order of graphitic degree sequence for these six chars can be ranked as PC char > ZY char > SF char > NM char > RS char > SD char. This validated the results obtained from XRD analysis. So the crystalline structure can be regarded as an important factor to evaluate gasification reactivities of different chars.

### 3.3. Differences in pore diffusion effects among CO$_2$ gasification with various chars

As stated above, under realistic entrained flow gasification conditions, the gasification temperatures are high and the particle size distributions are relatively wide. So gasification rates under these conditions may differ from that obtained under the condition of intrinsic reaction. Fig. 4 takes initial gasification rates of NM char and PC char as examples to show the difference between the gasification rate with the intrinsic reaction and that with relatively large particle sizes (~250 µm) and high temperatures (1123–1573 K). For both NM char and PC char (with the particle size of ~250 µm) gasification, initial gasification rates at relatively low temperatures (1123–1273 K) showed a linear correlation. However, the initial gasification rate at the temperature of >1273 K was below the straight line. The reason for this phenomenon is that the effect of pore diffusion might occur during gasification process. In addition, compared with gasification rates of very fine char particles (<46 µm), gasification rates of relatively large char particles were always slower. Based on these results, it can be concluded that gasification rates of samples are affected by pore diffusion under conditions of high temperatures and large particle sizes.

In order to quantify the effect of the pore diffusion on gasification and identify differences in pore diffusion effects among gasification with different chars, the effectiveness factor $\eta$ is used in this study. This method has been validated in the field of gasification (Barea et al., 2006; Mani et al., 2011). The effectiveness factor $\eta$ is defined as the ratio of the observed reactivity to the intrinsic reactivity and can be express by following equation which is conducted by Hong et al. (2000):

$$
\eta_{\text{eff}} = f_c \left( \frac{1}{3} \right) \left[ \frac{1}{\tanh(3\phi)} \right]^{-1}
$$

$$
f_c = \left[ 1 + \frac{\sqrt{2}}{2\phi^2 + 1/\phi^2} \right]^{0.5(1-n)^2}
$$

$$
\phi = \frac{n+1}{2} \left( \frac{2k_mC_{\text{a}}^{-1}}{D_{\text{eff}}} \right) \exp \left( -\frac{E_{\text{a}}/RT}{P^{0.5}} \right)
$$

Here, $\phi$ and $f_c$ are the Thiele modulus and the correction function, respectively. To validate Eq. (8) in this study, the intrinsic reaction rate constant ($k_m$) and the reaction gas concentration of solid particles surface ($C_{\text{a}}^{-1}$) are expressed by Arrhenius equation and the form of partial pressure, respectively. Hence, Eq. (8) can be deduced to following form:

$$
\phi = \frac{d}{6} \left( \frac{n+1}{2} \right) \frac{R \cdot T \cdot \rho_c \cdot A_{\text{int}} \cdot (1-x) \cdot \exp \left( -\frac{E_{\text{a}}/RT}{P^{0.5}} \right)}{M_c D_{\text{eff}}}
$$

where $d$ is the average particle size of the char. $\rho_c$ and $M_c$ are the density and the molecular weight of the particle, respectively. $D_{\text{eff}}$ is the diffusion coefficient including molecular diffusion and Knudsen diffusion. $A_{\text{int}}$ and $E_{\text{a}}$ are the pre-exponential factor and the activation energy obtained by intrinsic reaction, respectively. The order of the reaction ($n$), $A_{\text{int}}$ and $E_{\text{a}}$ can be calculated by Arrenhius equation. The results of these parameters are shown in Table 5. The orders of these coal or coke char reactions with CO$_2$ were from 0.09 to 0.48, similar to those calculated by others (Ahn et al., 2001; Roberts et al., 2010). The orders of two biomass reactions with CO$_2$ were 0.34 and 0.50, similar to those calculated by others (Barea et al., 2006; Ollero et al., 2002). The detailed order of reaction order sequence for various chars can be ranked as PC char < ZY char < RS char < SF char < NM char < SD char. This indicated that the sensitivity of the gasification rate to CO$_2$ partial pressure of biomass char was stronger than that of high rank coal or coke and similar to that of low rank coal. The activation energies were also similar to those listed in some literatures (Barea et al., 2006; Mani et al., 2011; Kwon et al., 1988). The detailed order of activation energy sequence for various chars can be ranked as PC char > ZY char > SF char > SD char > NM char > RS char. This indicated that the sensitivity of the gasification rate to gasification temperature.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$A/(s^{-1} MPa^{-n})$</th>
<th>$Ea/(kJ mol^{-1})$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD char</td>
<td>5.79 x 10^6</td>
<td>159.0</td>
<td>0.50</td>
</tr>
<tr>
<td>RS char</td>
<td>1.73 x 10^5</td>
<td>132.0</td>
<td>0.34</td>
</tr>
<tr>
<td>NM char</td>
<td>5.32 x 10^5</td>
<td>133.3</td>
<td>0.48</td>
</tr>
<tr>
<td>SF char</td>
<td>3.66 x 10^5</td>
<td>166.4</td>
<td>0.38</td>
</tr>
<tr>
<td>ZY char</td>
<td>2.88 x 10^5</td>
<td>168.3</td>
<td>0.19</td>
</tr>
<tr>
<td>PC char</td>
<td>1.64 x 10^5</td>
<td>176.5</td>
<td>0.09</td>
</tr>
</tbody>
</table>

![Fig. 4. Arrenhuius plots of gasification rates.](image-url)
of biomass char was weaker than that of high rank coal or coke and similar to that of low rank coal.

According to the method mentioned above, the calculated effectiveness factor $\eta$ vs gasification temperature curves for different chars with relatively large particle sizes ($\sim 250 \mu m$) are presented in Fig. 5. The results show that the effectiveness factor $\eta$ of all chars almost decreased as the gasification temperature increased. It is well known and also can be deduced by the definition of the effectiveness factor $\eta$ that the pore diffusion resistance increases as the effectiveness factor $\eta$ decreases. It means that the pore diffusion resistance of all the six chars increased with gasification temperature in this study. In addition, effectiveness factors of the other five chars with relatively large particle sizes are always lower than 1, except that of PC char (the effectiveness factor $\eta$ of PC char is equal to 1 when the gasification temperature is from 1123–1273 K). This phenomenon implies that the CO$_2$ gasification of PC char with relatively large particle sizes at the temperature of 1123–1273 K could be regarded as intrinsic, but the reaction of the other five chars under this condition was influenced by pore diffusion resistance. As stated above, CO$_2$ gasification of chars with very fine particles can be regarded as intrinsic. So it can be concluded that the pore diffusion resistance was also increased with the particle size (except PC char gasification under the condition investigated in this study).

It can also be seen in Fig. 5 that the order of $\eta$ values (obtained in all gasification temperatures investigated in this study) sequence for different chars was given as PC char $>$ ZY char $>$ RS char $>$ SF char $>$ SD char $>$ NM char. For coals and PC chars, the difference among their $\eta$ values is obvious. This was mainly attributed to the large difference among their intrinsic gasification reactivities, since parameters like $A_m$ and $E_{\text{tort}}$ had much effect on calculating the Thiele modulus $\phi$ and the effectiveness factor $\eta$. It can be concluded that the sample with higher gasification reactivity possesses stronger pore diffusion resistance. On the other hand, although the intrinsic gasification activity of biomass chars (RS char/SD char) was similar with or higher than that of NM char, $\eta$ values of these two biomass chars were always higher than NM char. This was attributed to the small density of these two biomass chars. It is well known that the density of coal char is always 3–5 times higher than that of biomass char. Therefore, the small density value of biomass char would lead to a small Thiele modulus value and high effectiveness factor $\eta$ value during calculating Eqs. (6)–(9). To sum up, differences in pore diffusion effects among CO$_2$ gasification with various chars were mainly attributed to different intrinsic gasification reactivities and physical characteristics of different chars.

4. Conclusions
Char particles of coals, biomass and coke prepared under the same condition were analyzed with multi-techniques to study their physical structures, chemical components and gasification reactivities. The crystalline structure is found to be an important factor to evaluate gasification reactivities of different chars and the crystalline structures of biomass chars are less order than those of coke/coal chars. In addition, gasification rates are affected significantly by pore diffusion under conditions of high temperatures and large particle sizes. Differences in pore diffusion effects among gasification with various chars are prominent and mainly attributed to different intrinsic gasification reactivities and physical characteristics.

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