Reactivity of pulverized coals during combustion catalyzed by CeO₂ and Fe₂O₃

Xuzhong Gong a,b,1, Zhancheng Guo a,c,* and Zhi Wang a

a State Key Laboratory of Multiphase Complex Systems, Institute of Process Engineering, Chinese Academy of Sciences, Beijing, China
b China Graduate University of Chinese Academy of Sciences, Beijing, China
c Key Laboratory of Ecologic and Recycle Metallurgy, University of Science and Technology, Beijing, China

A R T I C L E   I N F O

Article history:
Received 26 April 2009
Received in revised form 11 June 2009
Accepted 30 June 2009
Available online 25 July 2009

Keywords:
Ignition temperature
Combustion rate
Catalytic combustion
Reactivity

A B S T R A C T

Effects of CeO₂ and Fe₂O₃ on combustion reactivity of several fuels, including three ranks of coals, graphite and anthracite chars, were investigated using thermo-gravimetric analyzer. The results indicated that the combustion reactivity of all the samples except lignite was improved with CeO₂ or Fe₂O₃ addition. It was interesting to note that the ignition temperatures of anthracite were decreased by 50 °C and 53 °C, respectively, with CeO₂ and Fe₂O₃ addition and that its combustion rates were increased to 15.4%/min and 12.2%/min. Ignition temperatures of lignite with CeO₂ and Fe₂O₃ addition were 250 °C and 226 °C and the combustion rates were 12.8% and 19.3%/min, respectively. When compared with those of lignite without catalysts, no obvious catalytic effects of the two catalysts on its combustion reactivity were revealed. The results from the combustion of the three rank pulverized coals catalyzed by CeO₂ and Fe₂O₃ indicated significant effects of the two catalysts on fixed carbon combustion. And it was found that the higher the fuel rank, the better the catalytic effect. The results of combustion from two kinds of anthracite chars showed obvious effects of anthracite pyrolysis catalyzed by CeO₂ and Fe₂O₃ on its combustion reactivity.

© 2009 The Combustion Institute. Published by Elsevier Inc. All rights reserved.

1. Introduction

Coal combustion is one of the most important ways of coal utilization. To increase combustion rate and decrease ignition temperature, lots of studies have been carried out through adding various inorganic compounds. Hedden et al. [1] researched on the relationship between AAEM (alkaline and alkaline-earth compounds) and ignition temperature of several carbons. It is found that AAEM have high catalytic activity. With the same anions, the sequence of their activity is OH⁻ > CO₃²⁻ > Cl⁻ > SO₄²⁻. And if the alkaline ion is the same, the sequence of their activity is Cs⁺ > Rb⁺ > K⁺ > Na⁺ > Ba²⁺ > Li⁺ > Sr⁺ > Ca²⁺ > Mg²⁺ > Be²⁺. And if the alkaline ion is the same, the sequence of their activity is OH⁻ > CO₃²⁻ > Cl⁻ > SO₄²⁻. In addition, the catalysts studied were alkali halide and alkali phosphates [2], suggesting that if the anion is the same, the catalytic activity of halide is in the order of I⁻ < Br⁻ < Cl⁻ < F⁻. In the phosphates series, the catalytic activity was in the order of PO₄³⁻ < H₂PO₄⁻ < H₃PO₄.

But AAEM have strong negative effects on coal combustion, such as fouling, slagging and corrosion, which largely limit their application. Alternately, the rare-earth and transition-metal compounds have high catalytic activity, and especially CeO₂ and Fe₂O₃ have been widely used as catalysts [3], because they are inexpensive and have low toxicity as well. Many studies showed that CeO₂ and Fe₂O₃ have positive effect on combustion and breakdown of organic fuels and various carbons [4–6]. However, there are few reports on CeO₂ used as catalyst for coal combustion. On the other hand, though Fe₂O₃ is also a good catalyst for coal conversion [7], many researchers have found that it has no obvious catalytic effect at a temperature below 550 °C and that only when the temperature is above 550 °C, it has appreciable effect on coal combustion [8].

As we know, coal combustion consists of three processes, which are coal pyrolysis, pyrolysis gas and char combustion [9,10]. Among the three processes, pyrolysis is the most important aspects of coal behavior for it occurs in all major coal conversion processes, such as combustion, gasification, carbonization and liquefaction. Pyrolysis produces remarkable changes in chemical structure, surface morphology and porosity of the coal particle, which have a significant effect on the char reactivity. Char with high porosity and big specific surface area was prepared from anthracite with additives [11,12], which had strong adsorption capability and large contact area between char and oxygen.

In this work, effects of CeO₂ and Fe₂O₃, which were used as catalysts, on coal combustion were investigated. And catalytic effects of them on four different rank fuels were compared. In addition, combustion reactivity of chars from catalysts-adding-before and catalysts-adding-after in coking process was compared to disclose the effects of coal pyrolysis catalyzed by catalysts on its combustion reactivity. In addition, although the rare-earth
compounds are very expensive to be applied in the process of coal combustion catalyzed at present, these researches can achieve lots of fundamental information to develop catalysts with higher activity and low cost.

2. Experimental

2.1. Coal samples

Three types of Chinese coals: lignite, bituminous and anthracite, with different compositions and different mineral matter contents, were used in this work. All samples were ground to 0.15–0.10 mm, and the properties of the coal samples are listed in Table 1. The graphite is of spectral purity. Although demineralization process cannot destroy carbon skeleton structure of coal [13,14], it can increase organic functional group content and species due to the broken cationic bridges [14], such as –OH and –COOH. Thus, to maintain crease organic functional group content and species due to the bro-

2.2. Combustion

Combustion was carried out using a thermo-gravimetric analyzer (ZRY-2P, China). Coal sample (About 22 mg) was placed in an Al2O3 ceramic crucible (inner diameter 5 mm) and was burned under an O2 atmosphere (100 ml/min) at a heating rate of 15 °C/min from 100 to 1000 °C. In this paper, only the effects of catalysts on pulverized coal combustion reactivity were investigated, and comparisons of sample with and without catalysts combustion reactivity were made. Effects of other combustion conditions on reactivity were studied in previous papers, including heating rate, catalysts content, and oxygen flow [15,16].

Table 1 Properties of the coals.

<table>
<thead>
<tr>
<th></th>
<th>Lignite</th>
<th>Bituminous</th>
<th>Anthracite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximate analysis, air-dried basis (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>19.89</td>
<td>9.34</td>
<td>2.27</td>
</tr>
<tr>
<td>Ash</td>
<td>11.62</td>
<td>5.00</td>
<td>12.57</td>
</tr>
<tr>
<td>Volatile matter</td>
<td>31.32</td>
<td>32.76</td>
<td>10.77</td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>37.17</td>
<td>32.90</td>
<td>74.39</td>
</tr>
<tr>
<td>Ultimate analysis, air-dried basis (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>49.08</td>
<td>68.64</td>
<td>74.97</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>3.25</td>
<td>4.18</td>
<td>2.66</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.62</td>
<td>0.91</td>
<td>0.94</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.87</td>
<td>0.36</td>
<td>0.62</td>
</tr>
<tr>
<td>Oxygen (by difference)</td>
<td>14.57</td>
<td>11.57</td>
<td>5.97</td>
</tr>
<tr>
<td>Analysis of ash (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO2</td>
<td>41.12</td>
<td>32.56</td>
<td>48.72</td>
</tr>
<tr>
<td>Al2O3</td>
<td>17.79</td>
<td>10.53</td>
<td>32.59</td>
</tr>
<tr>
<td>TiO2</td>
<td>0.87</td>
<td>0.5</td>
<td>1.15</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>10.60</td>
<td>10.72</td>
<td>5.20</td>
</tr>
<tr>
<td>CaO</td>
<td>5.70</td>
<td>25.32</td>
<td>4.09</td>
</tr>
<tr>
<td>MgO</td>
<td>2.00</td>
<td>1.06</td>
<td>0.74</td>
</tr>
<tr>
<td>Na2O</td>
<td>2.90</td>
<td>2.91</td>
<td>0.96</td>
</tr>
<tr>
<td>K2O</td>
<td>1.67</td>
<td>1.05</td>
<td>0.86</td>
</tr>
<tr>
<td>P2O5</td>
<td>0.52</td>
<td>0.04</td>
<td>0.63</td>
</tr>
<tr>
<td>SO3</td>
<td>3.38</td>
<td>11.38</td>
<td>0.96</td>
</tr>
<tr>
<td>Others</td>
<td>2.62</td>
<td>3.93</td>
<td>4.10</td>
</tr>
</tbody>
</table>

2.3. Pyrolysis

The experiment was carried out to disclose effects of anthracite pyrolysis catalyzed by CeO2 and Fe2O3 on its combustion reactivity. Anthracite-raw, anthracite-CeO2 and anthracite-Fe2O3 were placed in a 40 mm inner diameter tube furnace and pyrolyzed under N2 at a flow rate of 2 L/min from room temperature to 1000 °C at 4 °C/min. Three cooled chars were ground to 0.15–0.10 mm and were designated as char-anthracite-raw, CeO2-adding-before and Fe2O3-adding-before, respectively. On the other hand, char-anthracite-raw (without catalysts) was mixed with CeO2 or Fe2O3, and Ce or Fe atom molar concentration is the same with that in CeO2/Fe2O3-adding-before, which was designated as CeO2/Fe2O3-adding-after. Their combustion reactivity was studied by a thermo-gravimetric analyzer in O2. Preparation of all samples was the same to guarantee the same physical property.

2.4. Evaluation of reactivity

Ignition temperature, combustion rate and burnout behavior were determined to evaluate coal combustion reactivity. The lower the ignition temperature and higher the combustion rate, the better the reactivity. Ignition temperature and combustion rate were determined by methods in Ref. [15]. When the DTG value was close to zero again, the corresponding time was considered as the burnout time (tB) of the samples. As shown in Table 2, the effects of catalysts on the burnout time of four fuels were slight; so, the burnout time cannot completely reflect burnout characteristic of the samples. In this work, the burnout index is used to evaluate the burnout characteristic, which can be described as follows [17,18]:

\[
D_i = \frac{(dw/dt)_{max}}{\Delta T_{1/2} \times t_i}
\]

where \((dw/dt)_{max}\) is the maximum combustion rate (mg/min), \(\Delta T_{1/2}\) is the zone of \((dw/dt)/(dw/dt)_{max} = \frac{1}{2}\) (min), \(t_i\) is the corresponding time of \((dw/dt)_{max}\) (min), and \(t_i\) is the burnout time (min). These data were obtained from DTG curves.

In addition, to reflect the char combustion reactivity, reactivity index is used to evaluate the combustion reactivity, which can be described as follows:

\[
R = \frac{V_{rate}}{T_{ignition}}
\]

where \(V_{rate}\) is the combustion rate of char samples (%/min), \(T_{ignition}\) is the ignition temperature of char samples (°C); \(R\) is the combustion reactivity of char samples (%/(min °C)). The bigger the \(R\), the higher the combustion reactivity.

Table 2 The parameters of burnout behavior of the coal sample with and without catalysts.

<table>
<thead>
<tr>
<th>Samples</th>
<th>((dw/dt)_{max}) (mg/min)</th>
<th>(\Delta T_{1/2}) (min)</th>
<th>(t_i) (min)</th>
<th>(t_f) (min)</th>
<th>(D_i \times 10^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignite-raw</td>
<td>43.27</td>
<td>3.43</td>
<td>9.57</td>
<td>13.65</td>
<td>9.55</td>
</tr>
<tr>
<td>Lignite-CeO2</td>
<td>41.56</td>
<td>3.93</td>
<td>11.53</td>
<td>15.72</td>
<td>5.83</td>
</tr>
<tr>
<td>Lignite-Fe2O3</td>
<td>49.58</td>
<td>2.63</td>
<td>9.92</td>
<td>13.65</td>
<td>13.91</td>
</tr>
<tr>
<td>Bituminous-raw</td>
<td>23.82</td>
<td>3.83</td>
<td>11.67</td>
<td>26.67</td>
<td>2.00</td>
</tr>
<tr>
<td>Bituminous-CeO2</td>
<td>37.29</td>
<td>4.73</td>
<td>10.63</td>
<td>26.67</td>
<td>2.78</td>
</tr>
<tr>
<td>Bituminous-Fe2O3</td>
<td>32.73</td>
<td>4.58</td>
<td>10.72</td>
<td>26.67</td>
<td>2.50</td>
</tr>
<tr>
<td>Anthracite-raw</td>
<td>24.59</td>
<td>6.23</td>
<td>26.98</td>
<td>36.67</td>
<td>0.40</td>
</tr>
<tr>
<td>Anthracite-CeO2</td>
<td>44.30</td>
<td>3.35</td>
<td>21.22</td>
<td>36.67</td>
<td>1.70</td>
</tr>
<tr>
<td>Anthracite-Fe2O3</td>
<td>34.84</td>
<td>2.93</td>
<td>21.53</td>
<td>36.67</td>
<td>1.50</td>
</tr>
<tr>
<td>Graphite-raw</td>
<td>35.87</td>
<td>5.22</td>
<td>45.18</td>
<td>53.33</td>
<td>0.29</td>
</tr>
<tr>
<td>Graphite-CeO2</td>
<td>40.01</td>
<td>3.35</td>
<td>38.60</td>
<td>53.33</td>
<td>0.58</td>
</tr>
<tr>
<td>Graphite-Fe2O3</td>
<td>33.55</td>
<td>4.55</td>
<td>39.17</td>
<td>53.33</td>
<td>0.35</td>
</tr>
</tbody>
</table>
3. Results and discussion

3.1. Effect of catalysts on ignition temperature

A number of parameters are known to influence the ignition temperature and ignition mechanism; these include the sample mass, particle size, volatile matter yield, and oxygen concentration. In addition to these variables, a number of system parameters related to the experimental conditions are important for the ignition behavior [17]. Obviously, ignition temperature is not a physical property of a fuel [19,20]. Our aim was not to propose a method of evaluation of ignition temperature. This work was based on a comparison attempt; that is, the same combustion process was kept for fuel raw and modified samples to see the impact of CeO2 and Fe2O3.

According to the TG-DTG, the ignition temperatures of lignite-CeO2, bituminous-CeO2, anthracite-CeO2, and graphite-CeO2 were 250 °C, 247 °C, 408 °C, and 631 °C, respectively. The ignition temperatures of lignite-Fe2O3, bituminous-Fe2O3, anthracite-Fe2O3, and graphite-Fe2O3 were 226 °C, 240 °C, 405 °C, and 631 °C, respectively. These results showed that except lignite the ignition temperatures of the other three fuels were decreased by the catalyzed combustion with CeO2 and Fe2O3.

A comparison of the reduction degree of the ignition temperature of the four fuels is shown in Fig. 1. As can be seen, the reduction in the ignition temperature of lignite-CeO2 was −24 °C, which showed that CeO2 had a negative effect on decreasing the lignite ignition temperature. The decreased amount of the ignition temperature for lignite-Fe2O3 was 0 °C, which indicated that Fe2O3 had no catalytic effect on lignite combustion. While for the other three fuels, the reduction degrees of the ignition temperature were positive and increased with the increase in the fixed carbon content. Therefore, the catalytic activity of the two catalysts on the ignition temperature was in the order of lignite < bituminous < anthracite < graphite.

Lots of bridge and branch bonds of molecular structure in lignite can be broken at low temperature [7], especially O-containing functional groups with higher activity, including −OH, −COH, and −C=O. A large number of volatile matters can be released from lignite and ignited easily at the first stage of combustion. As a result, the ignition temperature of lignite is determined by volatile combustion [19,20]. Lignite pyrolysis rate is, therefore, a very important factor for lowering ignition temperature. On the other hand, Morgan et al. [21–23] suggested that the presence of metal cations results in a decrease in the rate of volatile yield. The two most likely mechanisms are the cracking of volatiles to carbon-rich deposits and light gases and the polymerization of primary volatiles to non-volatile species. When lignite was impregnated with CeO2 or Fe2O3, improvement in cracking of volatiles matters and secondary char-forming reactions was seen, and secondary char sealed its pore structure and suppressed oxygen transfer.

However, the branch bonds become less and less from lignite to anthracite and diminished in graphite. On the contrary, the content of fixed carbon is increasing with increasing coal rank, which has lower thermal reactivity. So, the ignition temperatures of four fuels were determined from homogeneous reaction (volatile combustion) to heterogeneous reaction (fixed carbon combustion) little by little. Fig. 1 illuminates that the two oxides had positive catalytic effects on fixed carbon combustion. And the more the content of the fixed carbon, the better the catalytic effect. This conclusion confirmed the experimental results of Liu [8] that Fe2O3 had no effect on this coal combustion below 550 °C. The coal has lots of branch bonds of high thermal activity, and thus it was ignited at low temperature. Its ignition temperature was determined by the volatile combustion.

3.2. Effect of catalysts on combustion rate

Fig. 2 shows the weight loss of samples with combustion time. From Fig. 2a, it can be clearly seen that weight loss curve of lignite combustion was not changed by the two catalysts. Slopes of the three curves were uniform, and the curves of the two coal samples with catalysts became much flatter at the late stage of combustion. As can be seen from Fig. 3, the combustion rates of lignite-raw, lignite-CeO2 and lignite-Fe2O3 were 14.5%/min, 12.8%/min and 19.3%/min at the early stage of combustion, respectively. Fig. 2b showed that the combustion process of bituminous-raw was separated obviously into two stages, which were called the early stage and the late stage of coal combustion. And each stage can be subdivided into volatile and char combustion. For bituminous-CeO2 and bituminous-Fe2O3, the late stage of combustion was short, because part of char was burnt ahead. From Fig. 2b, the combustion rates of bituminous-raw, bituminous-CeO2 and bituminous-Fe2O3 were 7.3%/min, 17.1%/min and 15.6%/min, respectively.

As shown in Fig. 2c and d, weight loss of anthracite-raw and graphite-raw were both integrated process. But as they were impregnated with catalysts, combustion processes were separated into two stages. Furthermore, the combustion rates of anthracite-raw, anthracite-CeO2 and anthracite-Fe2O3 were 6.7%/min, 15.4%/min and 12.2%/min, respectively. On the other hand, the combustion rates of graphite-raw, graphite-CeO2 and graphite-Fe2O3 were 6.2%/min, 8.1%/min and 7.6%/min, respectively.

There was no obvious improvement in lignite and graphite combustion rates with CeO2 and Fe2O3 addition. However, those of bituminous and anthracite were improved greatly. Because combustion rate of lignite was controlled by the releasing rate of volatile during the pyrolysis process, pyrolysis cannot be improved by Fe2O3 as reported in previous research [24]. As for the graphite, it cannot be pyrolyzed, thus of which char with high activity cannot be prepared. On the contrary, pyrolysis of bituminous and anthracite was promoted with CeO2 or Fe2O3 addition, which resulted in gas increase and char prepared with high activity [9]. The crystalline structure in order was easily attacked by inorganic matter and developed distorted structure units [25]. So, the effect of catalytic combustion of the four fuels becomes better and better. These results indicated that the oxides had catalytic effects on the fixed carbon too.

From Fig. 3, because four fuels have different inherent structures, their catalytic combustion ranges were different. According
to the foregoing analysis, coal rank is one of the most important factors for catalytic combustion. For coal combustion, its ignition temperature and combustion rate was controlled by pyrolysis gas to char combustion from low to high rank coal, pyrolysis stage is therefore very important for coal combustion process. It cannot only release lots of pyrolysis gas, but also can prepare char with higher activity. With catalysts addition, coal pyrolysis stage was improved, thereby making the next combustion process easy.

In addition, the composition of coal ash had a very important influence on catalytic combustion [26]. According to Table 2, the contents of alkaline, alkaline earth and transition metal compounds in anthracite ash were less than those of lignite and bituminous. Anthracite itself had no good catalytic effect on combustion; so, addition of CeO2 or Fe2O3 would give an excellent catalytic ability.

3.3. Effects of catalysts on burnout behaviors

Fig. 4 shows DTG curves of all samples combustion process. The burnout indexes of all samples were calculated by using Eq. (1) and are listed in Table 2. The bigger the burnout index, the higher the combustion reactivity. From Table 2, it can be seen that the burnout index decreases with an increase in the fuel rank, indicating that combustion reactivity decreased from lignite-raw to graphite-raw. For a fuel, the burnout indexes of bituminous, anthracite and graphite with the two catalysts were bigger than their raw, which showed that two catalysts improved the three fuels combustion reactivity and accelerated fixed carbon combustion. Because the combustion of the three fuels was controlled by the fixed carbon, the catalytic effects on burnout behaviors may be a carrier of oxygen that promotes the oxygen transfer to the chars of them. The two catalysts acted as carrier for oxygen between char and CO2/CO. The rare-earth metals are under thermodynamics metastable condition [3]. Their compounds have many non-integrated structure, such as cavity, changed valence ion and lattice defect, adsorbing various active oxygen atoms in gas oxygen continually, including O3, O2−, O− and O2 [27]. In addition, transient metal oxide is a type of semiconductor, which also has a non-integrated structure, such as cavity, changed valence ion and lattice
It was interesting to note that the burnout indexes of anthracite-CeO$_2$ and anthracite-Fe$_2$O$_3$ were $1.7 \times 10^{-2}$ and $1.3 \times 10^{-2}$, respectively, which increased above 300% and 200% compared with that of anthracite-raw. However, lignite combustion was controlled by pyrolysis gas combustion, which results from pyrolysis rate and temperature. Lignite pyrolysis reactivity is higher than the other three fuels, which was improved by catalysts difficulty; the burnout index of lignite-Fe$_2$O$_3$ was higher than that of lignite-raw only, but CeO$_2$ cannot increase the burnout index of lignite-raw.

From the analysis mentioned above, effects of coal pyrolysis catalyzed by catalysts on its combustion reactivity were very important, which would directly influence pyrolysis reactivity and char structure. Due to anthracite structure, combustion characteristics of its char reflect anthracite combustion behaviors. So, it was very important to study the reactivity of anthracite char combustion catalyzed by catalysts for understanding the effects of catalytic pyrolysis on its combustion reactivity.

### 3.4. Effects of catalysts on anthracite char combustion reactivity

To show effects of anthracite pyrolysis catalyzed by catalysts on combustion reactivity, two kinds of anthracite chars combustion reactivity were investigated. Fig. 5 shows combustion reactivity indexes of chars prepared from different coking processes. Fig. 5 showed that the reactivity index of catalysts-adding-before was higher than that of catalysts-adding-after, and they all were higher than that of char-anthracite-raw (without catalysts).

Ignition temperatures of char-anthracite-raw, CeO$_2$-adding-before and Fe$_2$O$_3$-adding-before were 479 °C, 432 °C and 447 °C, respectively. On the other hand, ignition temperatures of CeO$_2$-adding-after and Fe$_2$O$_3$-adding-after were 447 °C and 458 °C, respectively, which also showed the positive effect of the catalysts on char combustion. However, ignition temperature of CeO$_2$-adding-after and Fe$_2$O$_3$-adding-after was higher than that of CeO$_2$-adding-before and Fe$_2$O$_3$-adding-before. Due to releasing of a large number of pyrolysis gases during anthracite pyrolysis catalyzed by CeO$_2$ and Fe$_2$O$_3$, chars with lots of pores and bigger specific surface
area were prepared [12], which resulted in higher combustion reactivity.

In addition, combustion rates of CeO2-adding-before and Fe2O3-adding-before were 14.9%/min and 25.0%/min, respectively. The combustion rates of CeO2-adding-after and Fe2O3-adding-after were 14.6%/min and 21.9%/min, respectively, while combustion rate of char-anthracite-raw was 14.5%/min. The results illuminated obvious effects of anthracite pyrolysis catalyzed by CeO2 and Fe2O3 on its combustion reactivity.

4. Conclusions

According to the results obtained in this paper, some conclusions can be drawn as follows:

(1) Ignition temperatures of lignite, bituminous, anthracite and graphite were decreased to different extents with CeO2 or Fe2O3 as catalysts, which are of the following order: lignite < bituminous < anthracite < graphite. In particular, the ignition temperatures of anthracite were decreased by 50 °C and 53 °C with CeO2 and Fe2O3 addition, respectively. However, that of lignite was almost not decreased.

(2) With CeO2 and Fe2O3 addition, the combustion rate of anthracite was increased to 15.4%/min and 12.2%/min, respectively, and the combustion time was advanced by about 200 s and 212 s accordingly.

(3) The burnout behaviors of all the samples from DTG curves indicated that effects of the two catalysts on four fuels burnout indexes were very different. Especially, the burnout index of anthracite-raw was increased above 300% and 200% with CeO2 and Fe2O3 addition.

(4) Combustion reactivity of the chars from anthracite pyrolysis was also improved. In detail, the ignition temperatures of CeO2-adding-before and Fe2O3-adding-before were 432 °C and 447 °C and their combustion rates were 14.9%/min and 25.0%/min, respectively. Their combustion reactivity was higher than that of CeO2-adding-after and Fe2O3-adding-after, revealing the effects of anthracite pyrolysis catalyzed by CeO2 and Fe2O3 on its combustion reactivity.

Acknowledgements

This work was supported by funds from the National High-Tech Research and Development Program of China (863 Program, 20060105220225).

References