A comparative study of the pyrolysis and combustion characteristics of sodium-rich Zhundong coal in slow and rapid processes

Zhong Huang | Na Li | Qulan Zhou | Duanyang Wang | Huaqiang Yin

1State Key Laboratory of Multiphase Flow in Power Engineering, Xi’an Jiaotong University, Xi’an, China
2Key Laboratory of Advanced Reactor Engineering and Safety of Ministry of Education, Tsinghua University, Beijing, China

Correspondence
Na Li, State Key Laboratory of Multiphase Flow in Power Engineering, Xi’an Jiaotong University, Xi’an, China.
Email: lyna@mail.xjtu.edu.cn

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Abstract
Coal with high content of alkali metal has limited use in the combustion process. The slow and rapid pyrolysis and combustion characteristics of sodium-rich Zhundong coal were investigated using a thermal gravimetric analyzer and one-dimensional drop-tube furnace. The results show that the process was complete when the final temperature exceeds 900°C in slow pyrolysis, while in rapid pyrolysis it lasts for short residence time in the whole furnace. The weight loss ratio in rapid pyrolysis was significantly higher than that in slow pyrolysis, and shows different trends at different reaction temperatures. There is an extremum value of weight loss ratio obtained at 800°C in rapid pyrolysis, which is accompanied by the maximum value for the diameter of pores and the minimum value for specific surface area. Most alkali elements are released from the solid product, and the amounts of released alkali elements in combustion are higher than that in pyrolysis process. The apparent activation energy in the two pyrolysis processes and release of alkali in combustion were evaluated using different models, which demonstrates that the alkali release trend in combustion is easier than that of pyrolysis.

KEYWORDS
alkali release, pyrolysis and combustion, rapid process, slow process, sodium-rich Zhundong coal

1 | INTRODUCTION

Coal is the most widely used fossil fuel in China. The coal reserves of the recently explored Zhundong Lower-Middle Jurassic coalfield in northwest China amount to 164 Gt.1 Many research have reported that Zhundong coal is a promising fuel for power plants due to its high volatility and low ash and sulfur content, and its rich reserves providing long-term energy support for China’s economic development, but the presence of high contents of alkali and alkaline earth metal elements, especially sodium, is the main problem for its use in the combustion process.2 Previous studies3-5 show that during coal or biomass combustion, sodium is more prone to direct vaporization because of its lower melting and boiling temperature and thus has a greater impact on fine particles. Many results6-10 indicated that alkali and alkaline earth metals released during the pyrolysis or combustion process can cause a variety of problems, including fouling, slagging, and corrosion, which has inhibited the utilizations of these fuels. Therefore, many studies have focused on the pyrolysis or combustion characteristics and the roles of alkali metal released during its use as fuel6,7,11-14. Therefore, it is necessary...
to analyze the pyrolysis and combustion characteristics of sodium-rich coal in different utility patterns.

Several researchers have investigated the pyrolysis and combustion behaviors of coal, which demonstrate that thermal gravimetric analysis (TGA) is an effective method to study the kinetics and to obtain the fundamental parameters of coal. As concerned, the weight loss ratio is an important index of pyrolysis, and it depends on the temperature and the heating rate of calefaction process. The heating rate in slow pyrolysis is low and it usually takes quite a long time to finish the study process. When the heating rate in the pyrolysis is more than 10²°C min⁻¹, the sample undergoes rapid pyrolysis.

In our work, both the processes have been adopted.

The aim of this work is to study the complete characteristics of sodium-rich coal, including slow pyrolysis using TGA, and rapid pyrolysis and combustion characteristics, as well as alkaline metal release characteristics in a one-dimensional drop tube furnace (ODDF). The kinetics study, carried out to all the processes, provides a theoretical reference for the utilization of sodium-rich coal.

2 | EXPERIMENTAL SYSTEMS

2.1 Thermogravimetric analyzer

The slow pyrolysis processes were performed in a thermogravimetric analyzer, Netzsch STA-409PC (Germany), with the precision temperature of ±2°C and microbalance sensitivity of 2 μg. The experiments were carried out at an atmospheric pressure, under a nitrogen atmosphere, with a flow rate of 100 mL min⁻¹, at linear heating rates of 5, 10, 20, and 30°C min⁻¹, and with different final temperatures of 500, 700, 900, 1000, and 1200°C. For all the tests, each sample mass was 10 mg, and then the release ratio as a function of time was recorded under different conditions.

For this work, the main factors, pyrolysis, temperature, heating rate, and particle size, were investigated. Table 1 shows the element analysis and industrial analysis of the raw coal, as well as the results of ash composition analysis. The ash fusion tests were performed under a weak oxidizing atmosphere according to the Chinese standard methodology (GB/T 219-2008, GB/T 219-1996). The deformation temperature of ash was 1270°C, the softening temperature was 1290°C, and the flow temperature was 1310°C.

2.2 One-dimensional drop tube furnace system

The rapid pyrolysis and combustion processes were conducted with different carrying gases in a one-dimensional drop tube furnace as shown in Figure 1. The furnace body includes four parts. Each part is 750 mm, and can be heated by 12 silicon molybdenum bars which are managed by temperature control unit with the rated temperature 1500°C. The inner diameter is 100 mm with the total height of 3 m. In the tests, the reaction conditions were set at an atmospheric pressure, nitrogen atmosphere, or air atmosphere, with a flow rate of 10 L min⁻¹. We designed a screw feeder, and the mass of coal power can be adjusted by a frequency converter. The coal supply quantity 80 g min⁻¹ is adopted for more product in experiment. The furnace has four sampling ports located at equidistant points along the vertical axis. The third sample port was used in most experiments as the local temperature was found to be stable than at other sample port locations. A water cooling sampling gun was inserted into the hole and the reaction product was obtained with the help of a vacuum pump. The product was cooled quickly to maintain their components and element contents.

X-ray diffraction (XRD) patterns were recorded on an XpertPRO (PANalytical) diffractometer, and X-ray fluorescence (XRF) analysis was conducted on a S4 PIONEER from Germany. These were used to detect the alkali metal compounds in ash and the content of main elements. By comparing the element contents in coal and sample products, we can obtain the alkali metal release trend in the pyrolysis and combustion process.

3 | RESULTS AND DISCUSSIONS

3.1 Slow pyrolysis characteristics

Small particles with diameter of 64 μm were tested in the temperature range from 30 to 1200°C, and the heating rate was set as 5, 10, 20, and 30°C min⁻¹, respectively. Figure 2 shows the release rate increases with the heating rate with the final temperature 1200°C. The derivative thermogravimetric (DTG) curves have the typical appearance of pyrolysis of coal materials. When the temperature exceeds 900°C, the weight loss is nearly constant, which means the pyrolysis process is almost complete. Three waves are observed in the DTG curves. The troughs between 100 and 200°C are the points of release of moisture and absorbed gas. The trough at 468°C is the point of volatile release. However, for the three curves over 900°C, another trough at about 800°C is likely to be the second splitting decomposition of the coke at high temperature. With lower heating rate, the temperature of inner and outer surface of the particle is similar, so the curves are not sharp in the whole process. However, the pyrolysis process takes more time, and hence more volatiles are released. But the volatiles precipitate out faster with the higher heating rate.

Two samples with different average diameters, 64 and 250 μm, have been tested as shown in Figure 3. The results indicate that the particle size has significant impact on the weight loss rate. We can see that the two peaks, representing
water release and volatile release, occur at the same temperature except for the small particles with lower heating rate. When the heating rate is high, the weight loss rate of small particles is higher than that of large particles in both two peaks, which should be attributed to high specific surface area of small particles. When the heating rate is lower at about 10°C min⁻¹, the phenomenon observed is reversed. The impact of internal surface area and heat transfer should be considered. For small particles at lower heating rate, the temperature of internal particle can be considered the same as the surface, so the internal pores of particles are the essential factor for pyrolysis. When the heating rate is high, the surface temperature increases quickly, but the internal temperature is still low for slow heat transfer in large particles, resulting

| TABLE 1 | Proximate and ultimate analyses results of coal and ash |
|----------|------------------------------------------------------|
|          | Proximate analysis (%)                               | Ultimate analysis (%)  |
|          | Vdaf (%)  | F, (%)   | A, (%)   | M, (%)   | C, (%)   | H, (%)   | N, (%)   | O, (%)   | S, (%)   | Fe2O3 (%) | Al2O3 (%) | CaO (%) | MgO (%) | SiO2 (%) | TiO2 (%) |
| Zhundong coal | 27.05  | 2.63     | 43.12    | 15.41    | 2.30     | 14.51    | 15.54    | 6.59    | 0.75    | 0.13      | 4.75      | 16.12    | 2.70     | 16.12    | 43.25    |
| Ash       | 6.43     | 0.91     | 4.32     | 4.32     | 0.96     | 3.00     | 3.00     | 4.32    | 3.00    | 0.96      | 3.00      | 4.32     | 3.00     | 4.32     | 3.00     |

The raw coal has been ground and sieved into two samples, with mean particle diameters of 64 and 250 μm.

FIGURE 1 The Drop Tube Furnace and Temperature Control System

FIGURE 2 Influence of heating rate on DTG pyrolysis profile
in the slow pyrolysis process. In addition, the primary reaction products may lead to the secondary reactions and carbon deposition at high temperature, which also has certain effect on coal volatile release.

3.2 Rapid pyrolysis characteristics

Samples were also tested in ODDF for rapid pyrolysis. It is very difficult to directly collect and measure moisture and volatile release of products in the pyrolysis process. The mass of ash in raw coal and the product remains constant during the reaction, so the release ratio of water and volatile can be deduced by the following equations.

The release ratio of water can be calculated by the following equation.

\[
M = \left(1 - \frac{A_0 \cdot M_m}{A \cdot M_0}\right) \times 100
\]  

(1)

where \(A_0\) is the ash content of raw coal before reaction, %; \(A\) is the ash content in the solid product after reaction, %; \(M_0\) is the water content of raw coal before reaction, %; \(M_m\) is the water content in the solid product after reaction, %.

The release ratio of volatile can be calculated by Equation (2).

\[
V = \left(1 - \frac{A_0 \cdot V_m}{A \cdot V_0}\right) \times 100
\]  

(2)

where \(V_0\) is the volatile content of raw coal before reaction, %; \(V_m\) is the volatile content in the solid product after reaction, %.

The residence time is a very important parameter in the rapid release process; so other sample ports and the end of the furnace have been used to collect the products to investigate the influence of residence time. According to our calculation, all the particles achieve the terminal setting velocity, and the residence time of different size particles in reaction area can be estimated. The influence of residence time on the rapid process is shown in Figure 4. When the residence time is more than 1 second, the release ratios of moisture are more than 90%. For the volatile, at the final pyrolysis temperature of 1000°C, the pyrolysis time of small particles with average size of 64 μm is about 0.6 seconds, which is far insufficient for large particles. This demonstrates that the volatile release ratio is significantly affected by the particle size and residence time.

Because of the importance of residence time, we also investigated the release rate of moisture and volatiles with different final temperatures as shown in Figure 5. It can be observed that the moisture release rate of large particles is significantly higher than that of small particles, which shows that large particles in rapid pyrolysis conditions has stronger water release ability. It is attributed to the short residence time of large particles with the same reaction conditions. The volatile release rate increases with the increase in the final temperature, but the large particles undergo a more steady process. The above results indicate that the particle size is a very complicated factor in the coal pyrolysis, and it is more significant in the rapid pyrolysis process due to the distribution and characteristics of pores in different size particles.

We have compared the weight loss ratio with different final temperatures in two processes as shown in Figure 6, and the results differ greatly. In slow pyrolysis (heating rate 20°C min⁻¹), the coal weight loss ratio increases with the temperature, but when the final temperature is more than 900°C, the weight loss ratio remains almost constant for complete
release. In the rapid pyrolysis process, the pore structure of coal char is more developed for higher heating rate, which is good for release of moisture and volatiles, so the weight loss ratio of rapid pyrolysis is higher than that of slow pyrolysis. After a large number of experiments, we find that in rapid pyrolysis when the final temperature is greater than 800°C, the weight loss ratio increases with the final temperature. But at about 800°C, the weight loss ratio has a minimum value. The possible reason is that at about 800°C, the released tar makes pore clogged which impedes the release of volatile. Tests of average pore diameter and specific surface area of coal char in the rapid process, as shown in Figure 7, have demonstrated this conclusion. At 800°C, although the diameter of pores reaches maximum, the specific surface area has a minimum value. As the pyrolysis temperature rises, tar is removed by evaporation, and the char surface area begins to increase, leading to higher weight loss ratio. When the final pyrolysis temperature is more than 1000°C, char is in the molten state, and the pore structure may collapse or even disappear, which reduces the average pore diameter.

3.3 | Alkali release characteristics in the rapid process

Alkali metal contents of rapid pyrolysis char and coal from different reaction conditions have been measured. From XRD results shown in Figure 8, the compound of Al and Si is aluminosilicate, which has high melting point and is difficult to volatilize. From XRF results, the contents of Al and Si are more, and we suppose that the absolute value of contents of Al and Si is reliable. The contents of alkali metal elements are very little, and for the measuring error and random error of the instrument, the accurate absolute value of the content of alkali metal element is hard to obtain. To avoid the measuring error and random error, we used the content of Si at 800°C as a standard to calculate the release quantity of alkali elements, and the mass of alkali metal can be calculated by the following equation:

$$M_i = M_{800} \frac{W_{Si}}{W_{Si}} \cdot \frac{W_i}{W_{800}}$$  \hspace{1cm} (3)

where $M_i$ is the mass of element M at reaction condition; $M_{800}$ is the mass of element M at 800°C; $W_{Si}$ is the measured mass ratio of element Si at reaction condition; $W_{Si}$ is the mass ratio of element Si at 800°C; $W_i$ is the measured mass ratio of element M at reaction condition; and $W_{800}$ is the mass ratio of element M at 800°C.

Comparing the results of coal and ash from the rapid process, we can obtain the following results. Figure 9 shows that the release quantity of sodium in the pyrolysis process can reach about 1.8 mg g⁻¹ coal with the increase in the residence
time and the final temperature. If the release quantity of alkali metal can be regarded as proportional to the reaction time, the slope of each curve is the alkali release rate, and we can see that the slope increases with the increase in the reaction temperature, indicating that the release rate of alkali metal increases with the reaction temperature. Comparing Figure 9(A) and (B), we can see the released sodium values of small particles are more than that of large particles. Small particles have larger specific surface area, which is beneficial to the release of sodium.

We also investigated other element contents in ash as shown in Figure 10. The mass fraction of elements S and Cl remained in ash first decreases and then increases with the temperature, but contents of Ca, Al, and Fe were almost steady. Figure 11 describes the release characteristics of alkali metals in both the pyrolysis and combustion process. It is observed that the released alkali in combustion is higher than that of the pyrolysis process. This conclusion reminds us of the reasonable utility way of coal with high content of alkali metals. Most of Na and K are released from the solid product, and the released fraction of K increases with the increase in the final temperature in both the processes, while the released fraction of Na reaches the maximum at 1000°C in combustion. This results show the similar release trend with elements S and Cl, which agree with the former studies that sodium potassium is released from coal in the form of sulfur and chlorine compounds.

### 3.4 Kinetic analysis

The pyrolysis kinetic model is established to get the kinetic parameters of the pyrolysis process. The fundamental rate equation used in all kinetic studies is expressed as Equation (4)

$$\frac{d\alpha}{dt} = k \cdot f(\alpha) = A \exp\left(\frac{-E}{RT}\right) \cdot f(\alpha)$$

where $k$ is the rate constant and $f(\alpha)$ is the reaction model, a function depending on the actual mechanism; $A$ is frequency factor, $s^{-1}$; $E$ is apparent activation energy, kJ mol$^{-1}$; $R$ is universal gas constant, 8.3145 J mol$^{-1}$ K$^{-1}$; and $T$ is temperature of particles, K.

Assume that the mechanism function $f(\alpha)$ is independent of temperature and reaction time, and only determined by the value of $\alpha$. Then integrating Equation (4), we obtain:

$$F(\alpha) = \int_{0}^{\alpha} \frac{d\alpha}{f(\alpha)} = \int k \cdot dt$$

**FIGURE 8** XRD curves of ash at different reaction temperatures

(A) Reaction temperature 800°C  
(B) Reaction temperature 900°C  
(C) Reaction temperature 1000°C  
(D) Reaction temperature 1100°C

1. SiO$_2$; 2. Ca$_2$(Al$_2$SiO$_7$); 3. CaSO$_4$; 4. Fe$_2$O$_3$; 5. Ca$_2$Al$_2$SiO$_8$; 6. (Na·K)Si$_3$AlO$_8$; 7. Ca(AlSi)$_2$O$_4$; 8. Ca$_2$(MgSi$_2$O$_7$); 9. Fe$_3$O$_4$
3.4.1 | Kinetic analysis of the slow process

For non-isothermal thermogravimetric analysis at a constant heating rate, $\beta = \frac{dT}{dt}$, thus Equation (5) can be written as Equation (6):

$$F(\alpha) = \frac{A}{\beta} \int_{T_0}^{T} \frac{e^{-\frac{E}{R \cdot T}}}{T} dT$$  

Using the Coats-Redfern\textsuperscript{20,21} integral method to analysis, we obtain:

$$\ln \frac{F(\alpha)}{T^2} = \ln \left[ \frac{AR}{\beta E} \left(1 - \frac{2RT}{E}\right) \right] - \frac{E}{R} \cdot \frac{1}{T}$$  

For the majority of the reactions, $\frac{2RT}{E}$ is far less than 1, so we believe $1 - \frac{2RT}{E} \approx 1$. Therefore, Equation (7) becomes

$$\ln \frac{F(\alpha)}{T^2} = \ln \left( \frac{AR}{\beta E} \right) - \frac{E}{R} \cdot \frac{1}{T}$$  

For slow pyrolysis, the equation of the mechanism of the three-dimensional diffusion model (Anti-Junders Equation)\textsuperscript{22} is chosen.

$$\begin{align*}
F_1(\alpha) &= \left[(1 + \alpha)^{\frac{3}{2}} - 1\right]^2, \quad T \leq T_{\text{max}} \\
F_2(\alpha) &= (1 - \alpha)^{-1} - 1, \quad T > T_{\text{max}}
\end{align*}$$  

where $T_{\text{max}}$ is the temperature when $\left(\frac{dw}{dt}\right)_{\text{max}}$ reaches maximum when the release rate reaches maximum.

According to the experiment, we divide the TG curve into five zones, which correspond to the following processes: water release, volatile initial release, slow pyrolysis, rapid pyrolysis, and stable pyrolysis. When the heating rate is low, the rapid and stable pyrolysis...
processes are combined, so the high temperature section is only \( T_{\text{max}} \approx 900°C \). Then, \( k_0 \) and \( E \) of each zone at heating rate 30°C min\(^{-1}\) and 5°C min\(^{-1}\) are calculated and listed in Table 2.

### 3.4.2 Kinetic analysis of the rapid combustion process

For the rapid combustion process, the coal sample will become soft and become a plastic material at high temperature, and the boundary of the interface disappears, so the following expression is adopted:\(^{23}\)

\[
F(\alpha) = (1 - \alpha)^{-1} - 1
\]  

(10)

Then Equation (5) becomes

\[
(1 - \alpha)^{-1} - 1 = k \cdot t
\]  

(11)

The mass reaction rate \( \alpha \) can be obtained from experiments, then the values of \( k \) at different final temperatures are evaluated. According to Equation (4), based on the simulation results as shown in Figure 12, the values of \( A \) and \( E \) can be calculated. For small particles, the apparent activation energy in the rapid process is 117.42 kJ mol\(^{-1}\), and the frequency factor \( A \) is \( 7.98 \times 10^4 \) s\(^{-1}\). For large particles, the apparent activation energy in the rapid process is 88.4 kJ mol\(^{-1}\), and the frequency factor \( A \) is \( 6.1 \times 10^3 \) s\(^{-1}\), which is different from other studies. The results show that Equation (8) is not a proper model for large particles in the rapid process. The same method is applied to sodium release data for small particles. The estimated apparent activation energy of small particles is 64.08 kJ mol\(^{-1}\) and the frequency

![Figure 12](image-url)
factor is 347.2 s$^{-1}$. The results are only a comparative study with the coal combustion data, and aimed to verify that the sodium release process is easier and fast in combustion.

3.5 Conclusions

In this paper, the slow pyrolysis, rapid pyrolysis, and combustion processes, as well as kinetic analysis of sodium-rich Zhundong coal have been studied at various reaction conditions, and the alkali release characteristics in the rapid process have also been investigated. The results show the two pyrolysis processes are different, and the weight loss ratio of rapid pyrolysis is higher than that of slow pyrolysis. Particularly, in rapid pyrolysis, the weight loss ratio at 800°C is a turning point, and at 800°C, the diameter of pores is maximum with the minimum specific surface area value. Alkali release tests, conducted in a one-dimensional drop tube furnace, show that the alkali metal elements release more in combustion, and sodium release increases with the reaction temperature. The pyrolysis kinetics analysis shows that the sodium release is inevitable in the combustion process indicating that for high-alkali metal coal proper utilization should be proposed.

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ORCID

Na Li  http://orcid.org/0000-0002-7975-4862

REFERENCES

1. Zhou J, Zhuang X, Alastuey A, Querol X, Li J. Geochemistry and mineralogy of coal in the recently explored Zhundong large coal field in the Junggar basin, Xinjiang province, China. Int J Coal Geol. 2010;82:51-67.
2. Song G, Song W, Qi X, Lu Q. Transformation characteristics of sodium of Zhundong coal combustion/gasification in circulating fluidized bed. Energy Fuels. 2016;30:3473-3478.
3. Lee SHD, Teats FG, Swift WM, Banerjee DD. Alkali-vapor emission from PFBC of Illinois coals. Combust Sci Technol. 1992;86:327-336.
4. Manzoori AR, Agarwal PK. The fate of organically bound inorganic elements and sodium chloride during fluidized bed combustion of high sodium, high sulphur low rank coals. Fuel. 1992;71:513-522.
5. Sui Z, Zhang Y, Yao J, Norris P, Cao Y, Pan W-P. The influence of NaCl and Na2CO$_3$ on fine particulate emission and size distribution during coal combustion. Fuel. 2016;184:718-724.
6. Li W, Wang L, Qiao Y, Lin J-Y, Wang M, Chang L. Effect of atmosphere on the release behavior of alkali and alkaline earth metals during coal oxy-fuel combustion. Fuel. 2015;139:164-170.
7. Wang CA, Jin X, Wang Y, et al. Release and transformation of sodium during pyrolysis of Zhundong coals. Energy Fuels. 2015a;29:78-85.
8. Li R, Kai X, Yang T, Sun Y, He Y, Shen S. Release and transformation of alkali metals during co-combustion of coal and sulfur-rich wheat straw. Energy Convers Manage. 2014;83:197-202.
9. Qi X, Song G, Song W, Yang S, Lu Q. Effects of wall temperature on slagging and ash deposition of Zhundong coal during circulating fluidized bed gasification. Appl Therm Eng. 2016;106:1127-1135.
10. Li S, Wei X. Behavior of alkali metal hydroxides/chlorides for NO reduction in a biomass reburning process. Energy Fuels. 2011;25:3465-3475.
11. Li GY, Wang CA, Yan Y, Jin X, Liu YH, Che DF. Release and transformation of sodium during combustion of Zhundong coals. J Energy Inst. 2016;89:48-56.
12. Lu Y, Wang Y, Xu Y, Li Y, Hao W, Zhang Y. Investigation of ash formation characteristics and migration of sodium during co-combustion of Zhundong coal and oil shale. Appl Therm Eng. 2017;121:224-233.
13. Song GL, Song WJ, Qi XB, Yang SB. Sodium transformation characteristic of high sodium coal in circulating fluidized bed at different air equivalence ratios. Appl Therm Eng. 2018a;130:1199-1207.
14. Song T, Hartge EU, Heinrich S, Shen LH, Werther J. Chemical looping combustion of high sodium lignite in the fluidized bed: combustion performance and sodium transfer. Int J Greenhouse Gas Control. 2018b;70:22-31.
15. Jayaraman K, Gökalp I. Pyrolysis, combustion and gasification characteristics of miscanthus and sewage sludge. Energy Convers Manage. 2015;89:83-91.
16. Wang X, Cotter E, Iyer KN, Fang J, Williams BJ, Biswas P. Relationship between pyrolysis products and organic aerosols formed during coal combustion. Proc Combust Inst. 2015b;35:2347-2354.
17. Darvell LI, Jones JM, Gudka B, et al. Combustion properties of some power station biomass fuels. Fuel. 2010;89:2881-2890.
18. Hayashi J-I, Iwatsuki M, Morishita K, Tsutsumi A, Li C-Z, Chiba T. Roles of inherent metallic species in secondary reactions of tar and char during rapid pyrolysis of brown coals in a drop-tube reactor. Fuel. 2002;81:1977-1987.
19. Hayashi J, Kawakami T, Taniguchi T, Kusakabe K, Morooka S, Yamura M. Control of molecular composition of tar by secondary reaction in fluidized-bed pyrolysis of a subbituminous coal. Energy Fuels. 1993;7:57-66.
20. Ebrahimi-Kahrizsangi R, Abbasi MH. Evaluation of reliability of Coats-Redfern method for kinetic analysis of non-isothermal TGA. Trans Nonferrous Met Soc China. 2008;18:217-221.
21. Coats AW, Redfern JP. Kinetic parameters from thermogravimetric data. *Nature*. 1964;201:68-000.

22. Li P, Yu Q, Qin Q, Lei W. Kinetics of CO2/Coal gasification in molten blast furnace slag. *Ind Eng Chem Res*. 2012;51:15872-15883.

23. Khawam A, Flanagan DR. Role of isoconversional methods in varying activation energies of solid-state kinetics: II. Nonisothermal kinetic studies. *Thermochim Acta*. 2005;436:101-112.

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