Analysis of energy consumption for lump coal degradation in melting gasifier

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ABSTRACT

The volume hypothesis, a theory about the energy scale of comminution, was adopted to analyze the degradation behavior of lump coal under different heating time. The breakage energy of chars was determined by a compression test, and the results show that the ultimate strength of chars decreased at the early stage during the heating process, resulting in a decrease of the char breakage energy. At the late stage during the heating process, the char breakage energy increased with the increase of heating time. The power consumption coefficients C_K of different chars were determined by a drum experiment, and then the char degradation behavior under different power consumptions was predicted. In addition, a gasification experiment was conducted to determine the gasification activation energy (with CO_2) of lump coal heated for different time. The results show that the gasification activation energy increased greatly at the early stage during the heating process, which showed opposite change to the breakage energy of chars. Furthermore, the internal temperature and heat changes of the bonded coal briquette were calculated by using an unsteady heat conduction equation. The large difference between the surface and the center temperatures of coal and the large amount of heat absorption at the early stage during the heating process may have a negative effect on the breakage energy of chars.

1. Introduction

Lump coal is used in the COREX/FINEX process, which is a new ironmaking technology offering a superior environmental performance compared with using a blast furnace[1-3]. The coking process is eliminated by the replacement with lump coal, and thus the pollutant is greatly reduced. However, the serious degradation of lump coal in the melting gasifier has been a concern since the running of the COREX C3000 plant in Baosteel. The main difference between lump coal and coke is that the strength of lump coal is much lower than that of coke, but at high temperatures, this can vary greatly with the coke forming process. The degradation behavior of lump coal is significantly affected by the reaction process of the coal. At high temperatures, coal can absorb a large amount of heat during the coke forming process, and the caking coal used in COREX could easily bind together during the coke forming process, and thus heat transfer was hindered by the increased coal char[4-6].

It has been observed that lump coal tends to move towards the high temperature region over 1073 K immediately when it is added to the top of a melting gasifier, enhancing fast pyrolysis of the lump coal and precipitation of tar from the lump coal[2,5]. In previous work[6], a large amount of residual coal was also found in most tuyere coke samples, illustrating that the lump coals added into the melting gasifier were not completely transformed into coke when they arrived at the tuyere region. Therefore, lump coal used in a melting gasifier has been selected to investigate the transformation process of the lump coal at high temperature (1273 K).

The quintessential and earliest energy consumption theories of comminution were the surface area hypothesis, volume hypothesis and crack hypothesis, which were proposed by Rittinger[7], Кирпичев[8] and Kick[9], and Bond[10] respectively, and they have been widely accepted to elucidate the mechanism of energy consumption for comminution[11]. Regarding comminution at room temperature, the energy consumption for the process of coarse comminution (particle sizes greater than 10 mm) has invariably been relatively accurately determined by the volume

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hypothesis in actual cases. The surface area hypothesis has proven to be more suitable for the fine grinding (particle sizes less than 200 μm) process, and the application scope of the crack hypothesis is somewhere in between[12]. In actual cases, the particle size of lump coal charged into the melting gasifier was approximately 20 mm. In this work, two volume hypotheses were adopted to analyze the degradation behavior of lump coal used in the COREX melting gasifier.

2. Experimental

2.1. Sample analysis

Table 1 shows the fundamental analysis of coal used in COREX process.

Table 1
Fundamental analysis of coals

Proximate analysis/wt.%				Elemental analysis/wt.%				Caking index $G_{R,I}$	Initial porosity $\gamma_0/\%$
FC_d	A_d	V_d	M_{ad}	C_d	H_d	N_d	O_d		
60.35	7.71	31.94	2.84	72.89	4.87	0.96	13	55	21.7

Note: FC_d, A_d, and V_d are the fixed carbon, ash and volatile content of the coal in dry basis, respectively; M_{ad} is the moisture content of the coal in air dry basis.

2.2. Coke forming experiment

A series of coke forming experiments were conducted, where 200 g of crushed lump coal with particle sizes ranging from 19 to 21 mm was placed in a stainless steel container. The experiment was carried out in a heat treatment furnace under dry nitrogen atmosphere. Before the experiment, 1 L/min of nitrogen gas was continuously blown into the container for 30 min, and then the coal sample container was sealed.

In actual cases, lump coal (298 K) was directly added to the top of a melting gasifier whose temperature was over 1073 K. In this experiment, the coal sample container was not put into the furnace until the furnace temperature reached 1273 K. The heating time of the lump coal was set to 30, 45, 60, 90, 120, 150, 180 or 240 min, and the heating time was counted from the time when the furnace temperature reached 1273 K until cooling commenced.

After the heating experiment, optical microscopy (Leitz, DAS, Germany) was used to determine the textural composition of different char samples, and the surface morphology of the char samples was observed by scanning electron microscopy (SEM).

2.3. Compressive and drum experiment

An electronic pressure testing machine (Instron, LD-YB-2, China) was used to test the compressive strength and elasticity modulus of different char samples, and each char sample was made into a cyl-

inder of the same volume (ϕ12 mm×12 mm). The ultimate strengths of different chars were defined as the compressive stress per unit cross-sectional area at the breaking moment of chars.

The degradation behavior of chars was examined using a rotating drum (2.2 kW), and the input energy was adjusted by the power consumption or revolutions of the drum. After each drum experiment, the average particle size of the chars was measured by a vibrating screen. Afterwards, the power consumption coefficient was obtained by the equation of Kick's volume hypothesis.

2.4. Gasification experiment

Different samples (<0.074 mm) prepared from the lump coals heated for different time were reacted with CO_2 in a thermogravimetric analyzer (Netzsch, STA409C). Each sample (10 mg) was heated to 1273 K at a heating rate of 10 K/min. The CO_2 flow rate was set at 60 mL/min to eliminate the influence of gas diffusion, and the gasification rate was considered to be controlled by the chemical reaction.

3. Results
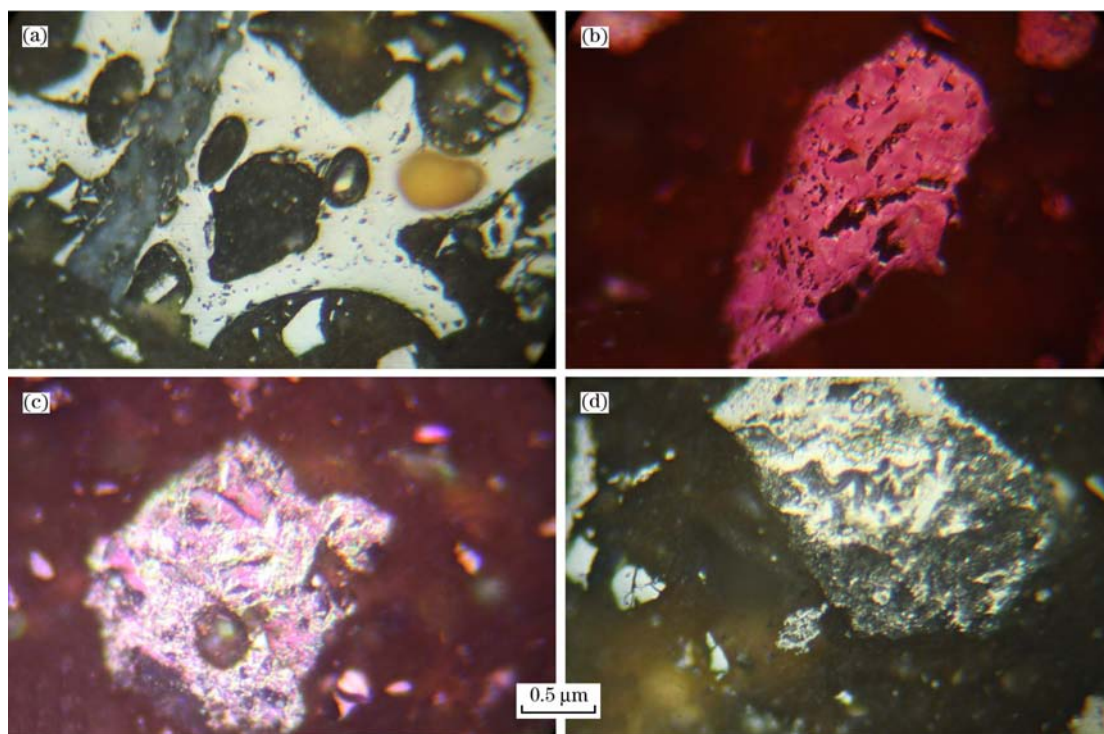
3.1. Structures of char

Fig. 1 shows the microstructure of char textures. The microstructure (minerals and impurities were not listed) and porosity (measured by mercury intrusion porosimetry) of different coal chars are summarized Table 2.

As shown in Table 2, the principal component of chars were isotropic and mosaics texture, and the coke structure components and porosity of chars increased with the increase of heating time. Fig. 2 shows the stereoscan photograph of lump coals heated for 0, 30, and 120 min.

As shown in Fig. 2, the number of pores increased with the increase of heating time. After heating for 30 min, a large number of pores are generated on the surface of char compared with that of the original coal.

3.2. Two volume hypotheses for char/coke degradation

Two volume hypotheses with different forms have been proposed by Кирпичев (Russian scholar) in 1874[8] and Kick (German scholar) in 1885[9] respectively, and they were both established on an identical physical foundation. According to the volume hypothesis, the energy consumption for material crushing is proportional to the volume of the material under identical technical conditions when the shape of the crushed product is similar to that of the raw material. The physical basis of the two hypotheses is that the stress is generated on the inside of any

(a) Isotropic;   (b) Anisotropic;   (c) Mosaics texture;   (d) Residual carbon particle.
Fig. 1.   Microstructure of char textures.

Table 2
Analysis results of coal char textures composition

Heating time/min	Coke/%						Residual coal/%	Porosity γ/%
	Isotropic	Anisotropic	Fine mosaics texture	Medium mosaics texture	Coarse mosaics texture	Residual carbon particle		
30	2.90	16.23	0	1.16	0	2.03	75.70	49.6
45	6.13	5.19	3.21	1.32	0.32	6.23	72.04	57.4
60	10.18	2.66	2.95	2.36	0.56	7.89	62.32	58.3
90	18.10	1.05	2.83	3.40	0.95	7.71	51.98	60.7
120	28.73	1.29	2.41	6.91	1.11	8.09	32.88	62.5
150	32.10	12.30	0	2.20	2.30	12.30	34.60	63.8
180	52.45	1.24	2.91	9.24	1.29	6.32	12.35	65.2
240	44.19	17.94	5.65	3.30	10.10	13.29	0.33	65.9
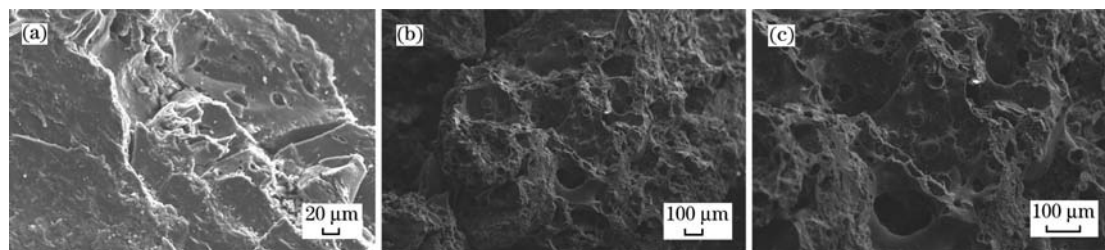
(a) 0 min;   (b) 30 min;   (c) 120 min.
Fig. 2.   Stereoscan photograph of lump coals heated for different time.

material and then leads to deformation over the whole particle under an external force. Thus, breakage within the material would occur in the case where the stress exceeds the ultimate strength of the mate-rial. In this work, these two volume hypotheses were adopted to elucidate the degradation phenomenon of char/coke, which has been widely considered to be a brittle material.

According to the Hooke's law, the strain rate of char can be calculated as follows:

$$\varepsilon = \frac{\sigma}{E} = \frac{\Delta l}{l} \tag{1}$$

where, σ is the stress, MPa; ε is the strain rate of char; E is the elasticity modulus of char, MPa; Δl is the amount of elastic deformation, m; and l is the length of char, m.

Then, the differential equation is obtained:

$$d(\Delta l) = d\left(\frac{l\sigma}{E}\right) = d\left(\frac{l \cdot F/S}{E}\right) = \frac{l}{ES} dF \tag{2}$$

where, F is the compressive stress, N; and S is the cross-sectional area of the char, m^2.

The energy consumption equation proposed by Кирпичев is derived as follows[8]:

$$W = \int_0^{l^*} F d(\Delta l) = \int_0^{F^*} F \frac{l}{ES} dF = \frac{1}{2} F^{*2} \frac{l}{ES} = \frac{\sigma^{*2} l S}{2E} = \frac{\sigma^{*2} V}{2E} \tag{3}$$

where, W is the breakage energy of chars, kJ; l^* is the length of char at broken moment, m; F^* is the ultimate compressive stress of char breakage, N; σ^* is the ultimate strength of the char, MPa; and V is the volume of the char, m^3.

Thus, the energy required for a unit volume of char breakage W_1 is expressed as:

$$W_1 = \frac{\sigma^{*2}}{2E} \tag{4}$$

Table 3 shows the parameters of char breakage energy obtained by the compression test and W_1 calculated by Eq. (4).

Table 3
Parameters of breakage energy of chars

Heating time/min	σ^* /MPa	E/MPa	W_1/(kJ · m^{-3})
0	2.23	3726	0.67
30	2.20	4784	0.51
45	2.74	4831	0.78
60	3.27	4863	1.10
90	3.96	4942	1.59
120	4.73	4928	2.27
150	5.65	5106	3.13
180	6.42	5157	4.00
240	7.12	5160	4.91

As shown in Table 3, the ultimate strength of the chars increased greatly with the increase of heating time, except for the char sample heated for 30 min. This phenomenon may be caused by the fast pyrolysis of lump coal at the early stage, which would lead to a sharp increase of porosity.

The ultimate strength of chars is considered to be related to the char texture and porosity. The formula usually used to express the strength of porous material is Eq. (5), and it has also been confirmed for

lump cokes[13,14]:

$$\sigma^* = \sigma_m^* \exp(-b\gamma) \tag{5}$$

where, σ_m^* is the strength of the matrix (maximum strength of char/coke when $\gamma = 0$); and b is the coefficient to quantify the effect of the pore volume fraction on the strength of the porous material.

The porosity of the raw lump coal was only 21.7%, as shown in Table 1. After being heated for 30 min, the char porosity was more than doubled to 49.6%, and in the following heating process, the porosity of the char increased only to 65.9% after heating for 240 min, as shown in Table 2. This is the main cause for the decrease of the ultimate strength of chars at the early stage, which leads to a decrease of W_1, indicating that serious degradation of lump coal would occur in the early coke forming process.

The degradation behavior of lump coal is described by another form of the volume hypothesis that was proposed by Kick as Eq. (6)[8,9]:

$$W_2 = C_K \lg i_T = C_K \lg \frac{d_0}{d_f} \tag{6}$$

where, W_2 is the power consumption for char degradation, (kW · h/kg); C_K is the power consumption coefficient, which is related to char properties for a specific crushing equipment, (kW · h/kg); i_T is the total crushing ratio; d_0 is the initial average particle size of the char, m; and d_f is the average particle size of the char after the crushing experiment, m.

In this work, a rotating drum was used to examine the degradation behavior of the chars. The rotating speed of the drum was 25 r/min, and the motor power was 2.2 kW. W_2 is determined by the revolutions of the drum during the experiment, and d_0 and d_f are determined by measuring the average size of char particles. Then, C_K is determined by the drum experiment. Fig. 3 shows the drum experiment for lump coals heated for 30 min. Using this method, C_K of chars heated for different time were obtained, as shown in Table 4.

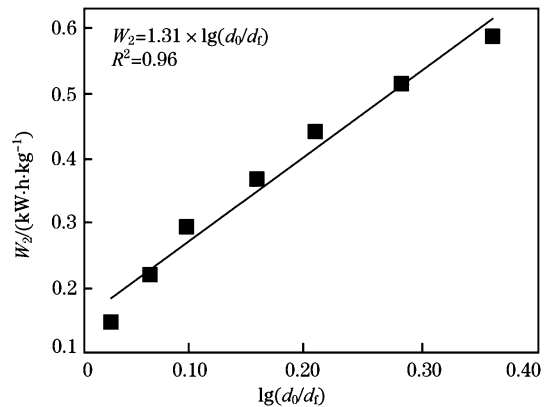C_K increased with the increase of heating time, ex-

Fig. 3. Drum experimental results of lump coal heated for 30 min.

Table 4
Power consumption coefficients of chars heated for different time

Heating time/min	0	30	45	60	90	120	150	180	240
$C_K/(kW \cdot h \cdot kg^{-1})$	1.32	1.31	1.47	1.62	1.95	2.76	3.21	3.83	4.86

cept for the char sample heated for 30 min, which is similar to W_1 calculated by Eq. (4). C_K could represent the degradation resistance of chars using the same crushing equipment.

To verify the results calculated by volume hypothesis, drum experiments with different chars were conducted. The experimental and calculated results of d_f were compared under power consumption levels of $W_2 = 0.220$ kW · h/kg (150 revolutions) and $W_2 = 0.368$ kW · h/kg (250 revolutions) and are shown in Fig. 4.
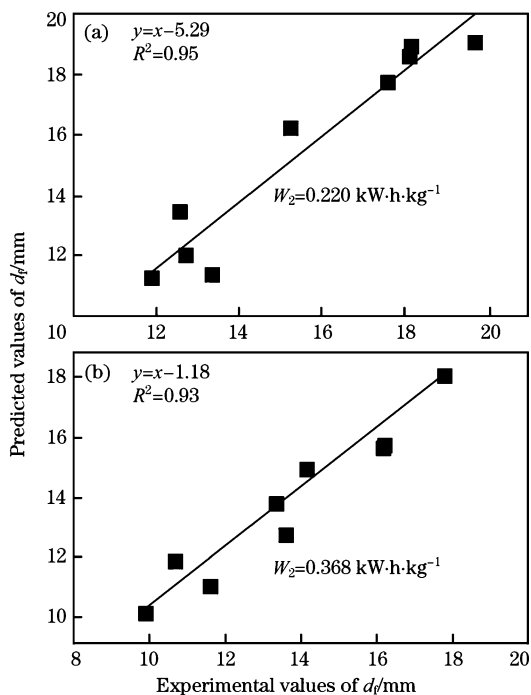

Fig. 4. Experimental and predicted values of d_f under different power consumptions.

As shown in Fig. 4, the predicted values of d_f are close to the measured values, which confirmed that the volume hypothesis is suitable for the analysis of lump coal degradation at high temperatures. Thus, the degradation behavior of lump coals heated for different time was predicted, as shown in Fig. 5.

d_f of chars decreased with the increase of input energy, but increased with the increase of heating time. An interesting phenomenon to note in Fig. 5 is that the more input energy for char degradation, the larger the differences were between lump coals heated for different time. As an example, in the case where
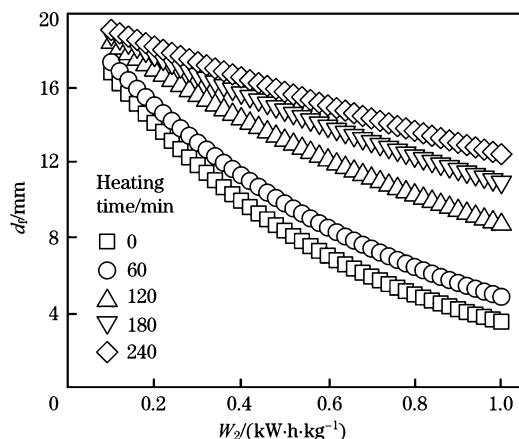

Fig. 5. Relationship between W_2 and d_f.

$W_2 = 0.1$ kW · h/kg, the difference of d_f between the raw coal (heating time is 0 min) and char heated for 240 min is only 2.27 mm. However, when $W_2 = 1.0$ kW · h/kg, the difference of d_f between the raw coal and char heated for 240 min increased to 8.96 mm. This result indicates that the input energy, which is related to the size of the melting gasifier and the smelting intensity, has a significant influence on the lump coal degradation at different coke forming stages. It should not be ignored when lump coals or semi-cokes were used to replace cokes in ironmaking production.

3.3. Results of gasification experiment

The gasification results of coal samples heated for different time from 5 min to 180 min are shown in Fig. 6. The initial reaction temperatures of different coals are obtained from Fig. 6 and listed in Table 5.

As seen from Fig. 6, the coal mass loss during the gasification process reduced with the increase of heating time. The longer the coking time of the lump coal was, the lower was its reactivity with CO_2. The initial reaction temperature rose with the increase of heating time, as shown in Table 5. This indicates that the fines generation of lump coal could be reduced by the preheating process.
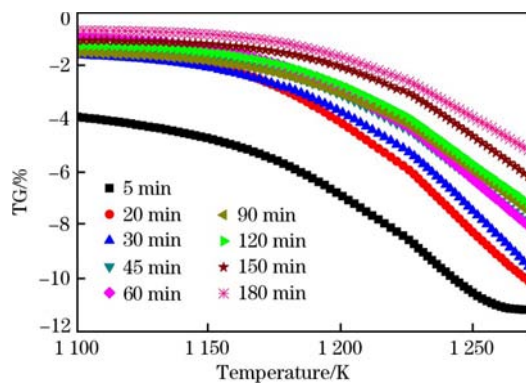

Fig. 6. TG curve of different coal chars reacted with CO_2.

Table 5
Initial reaction temperature of different coal samples

Heating time/min	5	20	30	45	60	90	120	150	180
Initial reaction temperature/K	837	861	873	878	884	886	887	895	902

For a non-isothermal process, following kinetic equations are used[15,16]:

$$\frac{d\alpha}{dt} = kf(\alpha) \text{ or } G(\alpha) = kt \tag{7}$$

$$G(\alpha) = \int_0^\alpha \frac{d\alpha}{f(\alpha)} \tag{8}$$

where, α is the conversion rate; t is the gasification time; k is the reaction rate constant; and $f(\alpha)$ and $G(\alpha)$ are the differential form and integral form of the mechanism function controlling the coal gasification, respectively.

The heating rate β of lump coal is a constant. Therefore, Eq. (7) can be expressed as:

$$\frac{d\alpha}{dT} = \frac{A}{\beta}\exp(-E_a/RT)f(\alpha) \tag{9}$$

where, A is the pre-exponential factor; E_a is the activation energy of coal gasification, kJ/mol; R is gas constant, J/(mol · K); and T is temperature, K.

According to the derivation and simplification of Eqs. (8) and (9), the Coats-Redfern integral equation is obtained[17-19]:

$$\ln[G(\alpha)/T^2] = \ln\left(\frac{AR}{\beta E_a}\right) - \frac{E_a}{RT} \tag{10}$$

Coal char gasification with CO_2 is regarded as a first-order reaction, and the regression model $G(\alpha) = 1-(1-\alpha)^{1/3}$ is used for data fitting. The data from different coal chars gasification are used in Eq. (10) for fitting with $1/T$ as the abscissa and $\ln[G(\alpha)/T^2]$ as the ordinate. By the slope and intercept of the fitting results, the activation energy and pre-exponential factor can be obtained. The activation energies of lump coals heated for different time are shown in Fig. 7.
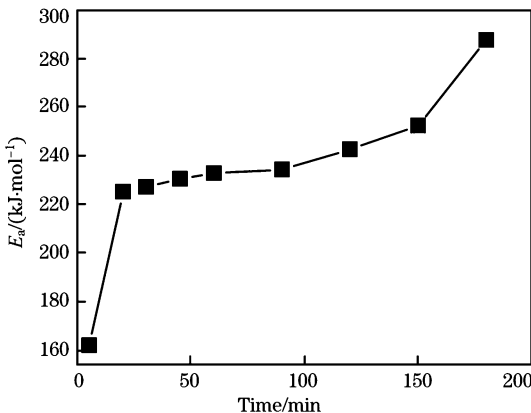

Fig. 7. Gasification activation energies of different char samples.

The low activation energy of lump coal in the earlier coke forming process (Fig. 7) shows the high reactivity with CO_2, which could result in a high fines generation rate of lump coal. The gasification activation energy of the coke forming process increased rapidly with the increase of heating time at the early stage, and then it did not increase rapidly again until it reached the final stage. The change of activation energy shown in Fig. 7 indicates that the reaction pattern of char samples may change with the increase of heating time. The gasification reaction occurs on the surface of coal at the early stage during the heating process, and then it takes place in the interior of the char, which may be caused by the fast pyrolysis of lump coal early during the heating process, which would lead to a sharp increase of porosity.

3.4. Effect of heat absorption on char breakage

The coal used in COREX is a kind of strong caking coal which is easy to bind together during pyrolysis at high temperature, and heat transfer inside the coal briquette occurs. In previous studies[20-23], it has been concluded that internal heat transfer is the rate-controlling factor of coal pyrolysis, which may have a significant influence on char breakage. In this work, the caking coal briquette was regarded as a sphere.

The heat conduction equation is given as follows[21,22]:

$$\frac{\partial(\rho c_P T)}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\lambda r^2 \frac{\partial T}{\partial r}\right) + q_v \tag{11}$$

where, ρ is density, kg/m^3; r is the sphere radius, m; λ is the thermal conductivity, W/(m · K); c_P is the specific heat capacity at constant pressure, kJ/(kg · K); and q_v is the intensity of the internal heat source, W/m^3.

q_v was given as follows[24]:

$$q_v = \rho_0 \Delta H \frac{\partial w}{\partial t} = -\Delta H \frac{\partial \rho}{\partial t} \tag{12}$$

where, ΔH is the specific heat effect of pyrolysis, $\Delta H = 300$ kJ/kg[24]; ρ_0 is the initial density of coal, kg/m^3; and w is the mass fraction of the volatile yield evolved up to time t.

λ and c_P of coal are given as[23-25]:

$$\begin{cases} \lambda = 0.23 \text{ W/(m · K)} & T \leqslant 673 \text{ K} \\ \lambda = 0.23 + 2.24 \times 10^{-5}(T-673)^{1.8} \text{ W/(m · K)} & T > 673 \text{ K} \end{cases} \tag{13}$$

$$\begin{cases} c_P = 1254 \text{ J/(kg · K)} & T \leqslant 673 \text{ K} \\ c_p = 1254 - 1.75(T-623) \text{ J/(kg · K)} & T > 673 \text{ K} \end{cases} \tag{14}$$

Initial condition: $T(r,0) = T_0$.
Boundary conditions[24]:

$$\frac{\partial T(r,t)}{\partial r}\Big|_{r=0} = 0, -\lambda \frac{\partial T(r,t)}{\partial r}\Big|_{r=R_s} = h[T_f - $$
$$T(R_s,t)] + \varepsilon_s\sigma_b[T_f^4 - T^4(R_s,t)] \tag{15}$$

where, T_0 is the initial temperature, $T_0 = 293$ K; T_f is the temperature of the surrounding gas, $T_f = 1273$ K;

ε_s is the system emissivity; h is the convective heat-transfer coefficient, W/(m² · K), calculated by $Nu = 2.0 + 0.6Re^{1/2}Pr^{1/3}$ [24]; Nu is the Nusselt number; Re is the Reynolds number; Pr is the Prandtl number; σ_b is the radiation constant; R_s is the equivalent radius of the coal, $R_s = \sqrt{\dfrac{3m}{4\rho\pi}}$; and the mass m and density ρ of the solid product were measured by experiment.

Table 6 shows the experimentally determined densities of the solid products.

Table 6
Density of different coal chars

Heating time/min	30	45	60	90	120	150	180	240
$\rho/$ (kg · m⁻³)	1056	980	863	802	745	735	710	702

For convenient calculation, only the first term in the infinite series of the analytical solution[21,22] was used.

$$\frac{\theta(x,t)}{\theta_0} = 2\frac{\sin\mu_1 - \mu_1\cos\mu_1}{\mu_1 - \sin\mu_1 \cdot \cos\mu_1}\exp(-\mu_1^2 Fo) \cdot \frac{1}{\mu_1 x}\sin(\mu_1 x) \qquad (16)$$

where, $\theta = T_0 - T_f$; $x = \dfrac{r}{R_s}$; $Bi = \dfrac{\alpha s}{\lambda}$; $Fo = \dfrac{at}{R_s^2}$; Bi is the Biot number, and Fo is the Fourier number; s is diathermy depth of the coal, m; a is the thermal diffusivity, m²/s; θ_0 is the initial excess temperature, K; and μ_1 is the eigenvalue of the differential equation.

The curves (nomogram) of $\dfrac{\theta_m}{\theta_0}$ ($r=0$) and $\dfrac{\theta}{\theta_m}$ change with Fo and Bi and can be obtained from Eqs. (16) and (17), and the relationship in Eq. (16) was adopted for each point in the sphere:

$$\frac{\theta}{\theta_0} = \frac{\theta_m}{\theta_0}\frac{\theta}{\theta_m} = \frac{T_m(t) - T_f}{T_0 - T_f} \cdot \frac{T - T_f}{T_m(t) - T_f} = \frac{T - T_f}{T_0 - T_f} \qquad (17)$$

where, $T_m(t)$ is the center temperature of coal at time t, K; and θ_m is the center excess temperature of coal, K.

Thus, the temperature of different points in the sphere can be obtained by checking the nomogram[21]. Fig. 8 shows the distribution of the internal temperature of coal char at different heating time.

To validate the calculation results, the predicted curve of the temperature history of the coal center is compared with the experimental data, as shown in Fig. 9. The experimental temperature was measured by a thermocouple plugged in the center of the coal samples through the gas exit port of the container. After the empty muffle furnace was heated to 1273 K,
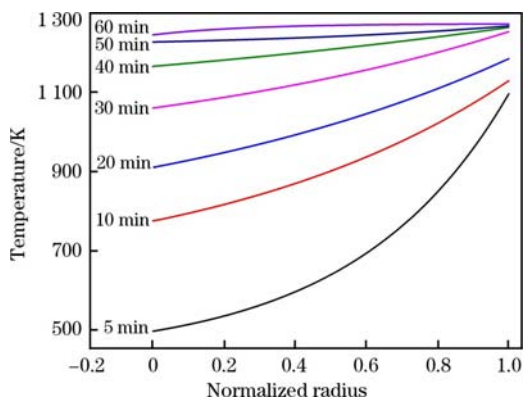

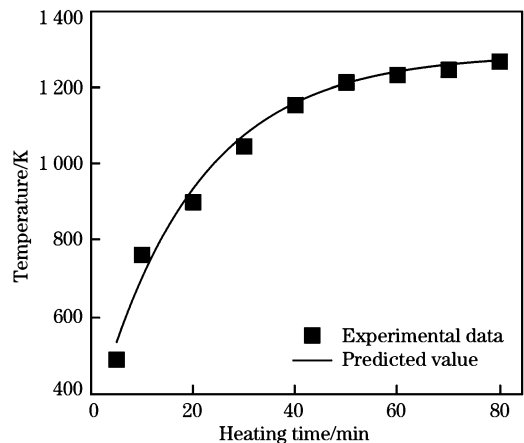**Fig. 8.** Radial profiles of coal temperature.

Fig. 9. Measured and calculated center temperature of coal.

the coal samples with the thermocouple were quickly pushed into the furnace. From the results in Fig. 9, the predicted temperatures fit well with the experimental data.

The heat absorption of coal char at different heating time could also be calculated by the measured values of coal temperature, and the results of heat absorption Q/Q_0 and W_1 calculated by Eq. (4) are both shown in Fig. 10. Q/Q_0 is the heat absorption ratio, where Q is the heat absorption at a given mo-
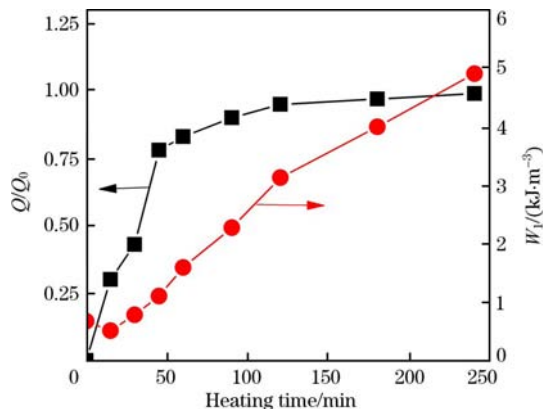

Fig. 10. Heat absorption and breakage energy of coal char at different heating time.

ment, and Q_0 is the total heat absorption.

It can be seen that the heat absorption of lump coal was concentrated at the early stage of coke formation, and the absorbed heat of the first 1/3 phase could account for 80% of the total heat absorption, and the heat absorption rate at the early stage is also higher than that at the late stage, as shown in Fig. 10.

As shown in Fig. 10, the char breakage energy decreased a little initially during the heating process. After heating for 30 min, W_1 increased with the increase of heating time. This result indicates that the large amount of heat absorption and the large difference between the surface and the center temperatures of the coal briquette at the fast pyrolysis stage of lump coal may have a negative effect on the strength of chars; this would cause serious degradation of lump coal in a melting gasifier.

4. Conclusions

(1) The char breakage energy decreased at the early stage during the heating process owing to the large number of pores produced by pyrolysis of coal. At the late stage during heating, the char breakage energy increased with the increase of heating time. The power consumption coefficients, which can be used to characterize the degradation resistance of chars, were determined by drum experiment, and the volume hypothesis was proven to be suitable for the characterization of char degradation by the verification experiment. The relationship between the average particle size of chars after crushing and the input energy was predicted by Kick's volume hypothesis, and the result revealed that the input energy, which is related to the size of the melting gasifier and the smelting intensity, has significantly different influences on the lump coal degradation at different coke forming stages.

(2) The gasification activation energy of lump coals at different heating time were determined by gasification experiments. Unlike the energy consumption for char breakage, the gasification activation energy of chars increased greatly with the increase of heating time in the early coke forming process. Furthermore, the internal temperature and heat changes of the coal briquette were calculated by using an unsteady heat conduction equation. The result shows that the coal briquette absorbed large amounts of heat at the early stage of the coke forming process,

which may have a negative effect on the strength of chars. There is a big difference between the surface and the center temperatures of the coal briquette at the early stage during heating, and this may be an important reason for the lump coal degradation in the melting gasifier.

Acknowledgment

References

[1] P. P. Kumar, Steel Res. Int. 80 (2009) 179-184.
[2] Q. H. Liu, K. Wu, ISIJ Int. 55 (2015) 947-951.
[3] Z. G. Luo, H. Zhou, T. Zhang, J. Iron Steel Res. Int. 22 (2015) 1098-1106.
[4] X. L. Wang, Iron and Steel Metallurgy, Metallurgical Industry Press, Beijing, 2013 (in Chinese).
[5] W. Shen, S. L. Wu, M. Y. Kou, J. Iron Steel Res. Int. 22 (2015) 200-206.
[6] Q. H. Liu, The Mechanism of Lump Coal Fission and Fines Generation in COREX Process, University of Science and Technology Beijing, Beijing, 2015 (in Chinese).
[7] R. P. Rittinger, Introduction of Comminution, Ernst & Korn, Berlin, 1867 (in German).
[8] D. X. Zhang, Journal of Northwest Institute of Light Industry 2 (1983) 46-54 (in Chinese).
[9] F. Kick, Law of Comminution Degree and Its Application, Arthur Felix Verlag, Leipzig, 1885 (in German).
[10] F. C. Bond, AIME Mining Engineering 193 (1952) 484-490.
[11] Z. D. Tao, S. H. Zheng, Powder Technology and Equipment, Chemical Industry Press, Beijing, 2010 (in Chinese).
[12] X. M. Liu, Y. X. Wu, J. F. Lu, G. X. Yue, Proceedings of the CSEE 33 (2013) 1-8 (in Chinese).
[13] H. Yamaoka, S. Suyama, ISIJ Int. 43 (2003) 338-347.
[14] K. Nishioka, S. Yoshida, Tetsu-to-Hagané 70 (1984) 343-349 (in Japanese).
[15] H. B. Zuo, H. W. Geng, J. L. Zhang, Int. J. Miner. Metall. Mater. 22 (2015) 363-369.
[16] A. Eberle, D. Siuka, C. Böhm, Steel World 7 (2002) 28-32.
[17] P. P. Kumar, D. Gupta, Ironmak. Steelmak. 33 (2006) 293-297.
[18] S. Richard, Fuel 82 (2003) 439-450.
[19] W. L. Zhan, K. Wu, Z. J. He, J. Iron Steel Res. Int. 22 (2015) 1078-1084.
[20] J. S. Chern, A. N. Hayhurst, Combust. Flame 46 (2006) 53-71.
[21] H. J. Zhang, Heat Conduction, Higher Education Press, Beijing, 1992 (in Chinese).
[22] Z. Z. Yao, M. D. Zheng, Coking Science, Metallurgical Industry Press, Beijing, 2011 (in Chinese).
[23] X. L. Liu, G. Wang, G. Pang, Fuel 106 (2013) 667-673.
[24] X. L. Liu, G. Pang, G. Wang, Energy & Fuels 25 (2011) 5729-5735.
[25] G. G. Fouga, G. D. Micco, A. E. Bohe, Fuel 90 (2011) 474-481.