ABSTRACT: The coke solution loss reaction was investigated by using a well-type Si-Mo rod electric furnace. The effects of the CO₂ flow rate, reaction time, loading mode, and loading amount of iron particles on the coke solution loss reaction were investigated. By comparing the SEM and EDS before and after the reaction of loaded iron particle coke, the reasons for the influence of loading mode on the coke solution loss reaction were explored, and the mechanism behind it was further explored. The experimental results show that there is a positive proportional relationship between the CO₂ flow rate and reaction time with coke solution loss reactivity. The adsorption and addition of iron oxide play an important role in promoting the coke solution loss reaction, but when the saturation point of iron oxide loading is exceeded (1%), the adsorption load of iron particles has little effect on the coke solution loss reaction. At the same reaction temperature, the carbon conversion of the adsorption method is 10% larger than that of the addition method. From the analysis of SEM, it can be seen that the mechanism of iron particles affecting the coke solution loss reaction is different under the two loading modes. In the addition method, some iron particles are wrapped in a coke pore wall matrix, so they cannot play a role. In the adsorption process, iron particles are uniformly distributed on the coke surface, which provide more effective catalytic active centers. In addition, when iron particles are loaded by the addition method, they participate in coke formation, which affects the coke structure and then affects the coke solution loss reaction. The iron particles in the adsorption method play a catalytic role in the coke solution loss reaction.

1. INTRODUCTION

Coke, as one of the important raw materials in blast furnace smelting, plays the main role of a heat source, reducing agent, and supporting column skeleton in a blast furnace to maintain good air permeability. The degradation of coke in a blast furnace is mainly due to the carbon loss reaction caused by CO₂ erosion, that is, the coke solution loss reaction \( \text{C}_{\text{coke}} + \text{CO}_2 \rightarrow 2\text{CO} \). The loose structure and the decreasing strength of coke affect the skeleton support and good permeability of a blast furnace. Coal blending coking is usually used in industrial production. When the composition of coal blending changes, the degree of the coal solution loss reaction also changes, considering that different types of coal have different degrees of solution loss reaction. Because the coke solution loss reaction is an endothermic reaction, the reaction equilibrium in the blast furnace moves with different coal blending. Therefore, it is of great theoretical and practical guidance to improve the quality of coke, strengthen the smelting, and improve the operation stability of blast furnaces. Previous studies on the influence of the coke solution loss reaction mainly focus on the selection of coking coal and the effect of coal blending technology and mineral composition in coal on the coke reaction. The main research direction of the minerals in coke is the circulation and enrichment of alkali metal and the influence of alkali metal and alkaline earth metal and its oxide; the study of transition elements and their oxides is mainly about their catalytic behavior (positive/negative catalysis) and their influence on the coke solution loss reaction. The study of iron oxides, on the one hand, is to explore their effect on coal pyrolysis; on the other hand, it is considered that they have a positive catalytic effect on the coke solution loss reaction, and the key factors may come from iron ions in iron oxides. Previous studies were simply based on the effect of iron on the coke solution loss reaction, which have not formed a systematic concept. In this paper, the variation of coke solution loss reactivity with reaction conditions is studied systematically, the influence of loaded iron particles on the coke solution loss reaction is explored, and the influence of...
different iron particle-loading modes are compared and analyzed.

2. RESULTS AND DISCUSSION

2.1. The Variation Law of Coke Solution Reactivity with Reaction Conditions. 2.1.1. Effect of Reaction Temperature. The coke solution loss reaction \((\text{C}_{\text{coke}} + \text{CO}_2 = 2\text{CO})\) is an endothermic reaction, so the degree of coke solution loss reaction will increase with the increase of temperature, as shown in Figure 1.

![Figure 1. Change of coke solution loss reactivity with temperature when the iron particle loading is 0.](image)

2.1.2. Impact of the CO2 Flow Rate. First, 18 g of coke sample with unloaded \(\text{Fe}_2\text{O}_3\) was weighed and put into a corundum crucible. A well-type silicon–molybdenum rod furnace was used for program heating. After the temperature reaches 400 °C, the nitrogen cylinder valve is opened, and the air in the nitrogen discharge device is first injected. The temperature is raised to 1200 °C under the protection of nitrogen, and the temperature is stabilized for 10 min. Nitrogen is cut off, and carbon dioxide gas is used. Different flow rates are set according to experimental requirements, and the reaction is continued for 1 h. After the reaction, the sample was naturally cooled to below 100 °C under the protection of nitrogen, then weighed, and recorded. The experimental setup and flow chart are shown in Figure 9. Figure 2 shows the changes in coke reactivity at different CO2 flows. It can be seen that the carbon conversion increases with the increase of CO2 flow, but the relationship is not linear. The gasification reaction of coke and carbon dioxide is a typical noncatalytic gas–solid reaction. The noncatalytic gas–solid reaction not only takes place on the surface but also goes deep into the solid particle crystal, which is a kind of bulk reaction. With the increase of the reaction capacity of coke and carbon dioxide, the mechanical strength (i.e., thermal strength) will become worse, which endangers the permeability and permeability of the lower part of the blast furnace. The diffusion of carbon dioxide will be affected by the deterioration of coke’s mechanical strength, so Figure 2 does not show a linear relationship.

2.1.3. Impact of Reaction Time. The coke sample of unloaded iron oxides was measured to be 18.0 g, the controlled reaction condition was CO2 with a flow rate of 0.625 L/min, the reaction temperature was 1200 °C, and the effect of reaction time on the coke solution loss reaction was studied. The results are shown in Table 2. It can be seen that carbon conversion increases over reaction time. The rate of carbon conversion can be calculated according to eq 1

\[
\text{Conversion Rate} = \frac{\text{conversion}_2 - \text{conversion}_1}{t_2 - t_1}
\]

From the results of the conversion rate, it can be seen that the degree of variation of coke solution loss reaction in different reaction stages is different. Because the solution loss reaction of coke should be carried out on the surface active sites in the particles, it is affected by the specific surface area of the reaction. The carbon content in the initial stage of the reaction is sufficient, and the corrosion of coke by CO2 is serious. As the reaction progresses, the surface area increases with the expansion of coke pores, so the reactivity increases at a high rate. As the reaction continues, the surface area increase rate is slowed down due to the collapse of the coke pore wall, so the reactivity increase rate decreases.13–15 In different reaction stages, the competitive effects of pore expansion and pore wall collapse lead to the increase of the coke solution loss reaction rate, as shown in Table 1.

![Figure 2. Changes of coke reactivity under different CO2 flows.](image)

Table 1. Effect of Reaction Time on the Coke Solution Loss Reaction

| reaction time/h | carbon conversion/% | conversion rate/%·h−1 |
|----------------|---------------------|----------------------|
| 0.5            | 22.8                | 45.6                 |
| 1.0            | 36.1                | 26.6                 |
| 1.5            | 54.2                | 36.2                 |
| 2.0            | 66.1                | 23.8                 |

2.2. Effect of Adsorbed Loaded Iron Particles on the Coke Solution Loss Reaction. The adsorption loading of iron oxides was 0.3, 1, 3, and 5%, respectively. Some Fe3+ particles were reduced to metallic iron after the reaction. The substance called iron particles in the experiment is the mixture of Fe, Fe3+, and Fe2+. The effect of adsorbed iron particles on carbon conversion (the optimum reaction conditions were determined by the experimental results: the reaction temperature was 1200 °C, the CO2 flow was 0.625 L/min, and the
reaction time was 1 h) was studied by the coke solution loss reaction experiment. The results are shown in Figure 3.

Figure 3. Effect of Fe particles loaded by the adsorption method on the coke solution loss reaction.

It can be seen that the coke conversion increases with the increase of reaction temperature under the same adsorption load of iron particles. The coke reaction increases with the increase of iron particle adsorption load at the same reaction temperature. When the loading of adsorbed iron particles is low (<1%), the solution loss reaction of coke carbon increases rapidly, and when the load is higher (>1%), the carbon conversion increases obviously, and the conversion rate of coke is close to that of coke carbon under 3 and 5% loadings. This indicates that there is a saturation point (1%) in the adsorption iron particle load, beyond which the influence of iron particles on the coke solution loss reaction basically does not increase even if the iron particle adsorption increases substantially.

2.4. Influence of Loading Mode of Iron Particles.

2.4.1. Comparison of the Effects on Coke Solution Loss Reactivity. Figure 5 shows the difference of coke reactivity under two loading modes when the iron particle load is 1.649%. The results show that the influence of different loading modes on the coke solution loss reaction is different under the same iron particle load, and the shadow effect of the adsorption method on the coke reaction is greater than that of the addition method. The Fe-containing phase in coke has strong interactions with the solution loss reaction. For example, at 1200 °C, the reaction of coke carbon can be increased from 31.5 to 47.5% by the addition method and to 54.5% by the adsorption method.

2.4.2. Comparison of Microstructure Analysis of Coke. If only the catalytic effect of iron particles is analyzed, when the loading of iron particles is the same, the influence of the two loading modes on the coke solution loss reaction should be basically the same, but the results of Figure 5 show that the influence of the adsorption method is greater than that of the addition method. In order to further explore the reasons, the coke addition method and adsorption method with an iron particle loading of 1.649% (prepared according to the method in Section 4.3) were selected for scanning electron microscope (SEM) analysis. The results are shown in Figure 6. It can be seen that iron particles loaded by the addition method exist in coke in the form of particles containing iron elements, and some of them are wrapped in a coke pore wall matrix, while when iron particles are loaded by the adsorption method, high dispersion is formed and evenly distributed on the surface of the coke matrix. The active center formed by the iron particle surrounded by the pore wall matrix of coke by the additive method can only play its role when it is exposed to the solution loss reaction of coke. Therefore, under the same iron particle loading, adsorption can provide more catalytic active centers for the solution loss reaction, which is the main reason why the adsorption method has more influence on the coke solution loss reaction than the addition method.\textsuperscript{16,17}
Samples with an adsorption load of 1.649% Fe₂O₃ were prepared according to the method mentioned in Section 4.3. The two samples were treated in the addition and adsorption methods, but the same amount of Fe₂O₃ (1.649%) reacts at...
1100 and 1400 °C. Figure 7 shows the SEM diagram of coke after the reaction of the two loading modes at different temperatures. The red circles are iron pellets. By comparing the SEM images at 1100 and 1400 °C, it can be found that when the temperature rises, the stomatal damage is more serious, the number of spherical particles increases, the cracking is serious, and the coke structure is more loose.18,19 The mineral phase will cover pore walls and the coke surface. Because of the existence of iron particles, the coke with the adsorption method has more surface crack centers, and the adsorbed coke can provide more catalytic active centers, the reaction is greater, and the coke structure is looser after the reaction. After the reaction at 1400 °C, the pore structure of the two kinds of coke is destroyed more seriously, accompanied by a large number of spherical particles. With the increase of reaction temperature, the number of spherical particles increases obviously. The electron energy spectrum analysis of spherical particles (EDS) is shown in Figure 8.

![Figure 8. EDS analysis of spherical particles.](image)

Combined with the reduction characteristics of iron oxides and EDS analysis, it is considered that the spherical particles are mainly iron. After the high temperature reaction, the spherical particles of the addition method are embedded in the coke microcracks or wrapped by the coke matrix, while the spherical particles of the adsorption method are dispersed on the surface of coke.20

2.4.3. Comparison of the Influence Mechanism of Iron Particle Loading Mode on the Coke Solution Loss Reaction.

From the above analysis, it can be seen that the two loading modes can promote the coke solution loss reaction; that is, iron particles have a positive catalytic effect on the coke solution loss reaction, but the influence of the two loading modes on the coke solution loss reaction is different. In fact, this is because the two influence mechanisms are different. The influence mechanism of iron particles loaded by the addition method on the coke reaction can be explained from the following two points.

1. The structure of coke is affected by adding iron particles, so as to improve the solution loss reaction of coke. In the process of coal coking, colloids are produced, and the isotropic liquid gradually increases. The condensed cyclic aromatic hydrocarbon molecules generated by decomposition are arranged in the liquid phase, generating optical anisotropy. The lower the degree of anisotropy, the greater the coke reactivity. When loaded iron oxides are added, they will participate in the coking process of coal. The attraction between the positive charge part of iron oxides and the electronegative aromatic molecules weakens the force between aromatic molecules and hinders their arrangement, thus affecting the formation of the mesophase, reducing the anisotropy of coke, and improving the reactivity of the coke solution loss reaction. Therefore, the greater the load of iron oxides, the greater the impact on coke reactivity, and the participation of iron particles in the coal coking process will inevitably lead to the phenomenon of some iron particles being wrapped by the coke matrix.

2. In the coking process, the presence of iron oxides makes them become the crack center, leading to coke cracking and increasing cracks. Moreover, iron particles and coke anisotropic tissues combine to form interlayer compounds, increasing the interval between layers, and volume expansion leads to crack and generation of lifetime microcracks. The increase of microcracks leads to the increase of specific surface area and the improvement of coke reactivity. The mechanism of the effect of adsorbed iron on the coke solution loss reaction is that the adsorbed iron particle forms a high dispersion on the surface of the coke matrix in the molecular form and only acts as a catalyst for the coke solution loss reaction but has no effect on the coke structure. The catalytic mechanism is that iron particles are evenly distributed on the surface of coke, so that they can fully come into contact with carbon atoms at the active position on coke and adsorb CO2 and oxygen migration occurs, forming the reaction intermediate C(O). C(O) is the decisive factor of catalysis. C(O) desorption generates the product CO, which improves the reactivity of the coke solution loss reaction.21

3. CONCLUSIONS

In this paper, the influence of iron oxides on the coke solution loss reaction is studied from the aspects of coke reactivity, reaction conditions, and different loading modes. The microstructure of coke and the existence of iron-bearing minerals are also analyzed through SEM and XRD. The following conclusions can be drawn:

1. At 1200 °C, conversion of coke increases with the increase of the CO2 flow rate from 30 to 50%, but the conversion rate decreases obviously.

2. Loaded iron particles (adsorption and addition) increase the solution loss reactivity of coke. The effect of adsorbed iron particles on the coke solution loss reaction exhibits a loading saturation point (1%). Even if the adsorption load of iron particles is greatly increased, the coke reaction will no longer be affected by the increase of iron particle adsorption load.

3. The impact of the iron particle load formula on coke solution loss reactivity varies, and the adsorption method has a greater impact on the coke solution loss reaction than the addition method.

4. High temperature will cause serious damage to the structure of coke. With the increase of temperature, the strength of coke and particle size decreases significantly. High temperature will also damage the pore wall structure of coke, causing it to collapse seriously and increase surface microcracks. After the reaction, the iron particle loaded into coke is reduced to metallic iron, which mostly exists in the form of...
spherical particles, and its quantity increases with the increase of the reaction temperature.

4. THE EXPERIMENTAL PART

4.1. Coke Sample. The untreated coal is made by mixing different kinds of coal in a certain proportion. The percentage of coordinate coals is shown in Table 2. The proximate and ultimate analyses of the untreated coal are provided in Table 3. Table 4 shows the ash analysis results of coke; according to the needs of the experiment, the coke was processed into particles with a diameter of 3~6 mm as the experimental samples.

4.2. Determination of the Coke Solution Loss Reaction. As illustrated in Figure 1, the coke sample was put in an alumina reactor inserted into an electric furnace for the gasification reaction. The reactor consists of a gas ducting tube and a sheath. The coke sample was located at the bottom of the gas ducting tube on an alumina plinth to support the sample. The temperature of the electric furnace is detected and controlled using a JLD programmable temperature controller (Figure 9). A proper amount of coke with a particle size of 3~6 mm was put on the alumina plinth and placed in a well-type Si–Mo rod electric furnace for the reaction. The heating rate is controlled at 8~16 °C/min. When the coke temperature reaches 400 °C, nitrogen is introduced into at a flow rate of 0.8 L/min to protect the coke from burning at high temperature and prevent burning loss at high temperature. The temperature reaches the reaction temperature and is allowed to remain constant for 10 min; next, the nitrogen gas is cut off, carbon dioxide is introduced, and then the rotor flow meter is adjusted to the experimental flow rate to start the reaction. After the reaction, heating is stopped and carbon dioxide is cut off and changed to nitrogen; when the coke is cooled below 100 °C, nitrogen flow is stopped and the coke is poured out for weighing.

The carbon conversion reflects the solution loss reaction ability of coke and is calculated according to formula 2.

\[
\text{Conversion} = \frac{m_{2} - m_{1}}{m_{1}} \times 100\% 
\]

In the formula, \(m_{1}\) stands for the mass of coke before the reaction, \(g\); \(m_{2}\) is the mass of coke after the reaction, \(g\).

4.3. The Adsorption Method to Load Iron Particles. The experimental samples are selected with Baosteel large-scale production coke samples, the properties of which are shown in Table 3. In order to adsorb iron oxides into coke, gas phase adsorption or liquid phase adsorption can be used. Because it is not easy to adsorb iron oxides with coke in the gaseous state, liquid phase adsorption is used in this experiment.

First, \(\text{Fe(NO}_3\text{)}_3 \cdot 9\text{H}_2\text{O}\) is added to water to prepare \(\text{Fe(NO}_3\text{)}_3\) solution of a certain concentration, and then, a certain amount of coke samples with a particle size of 3~6 mm was weighed and put into the prepared solution and heated to boil in a thermostatic water bath (90 °C), stirring constantly until the solution is completely dried. It should be noted that the stirring speed should be low to prevent uneven adsorption and coke particle splashing caused by too much speed, which will affect the experimental results. The stirring speed in this experiment was 350 rpm.

After steaming and drying, the coke sample was put into an oven for drying for 2 days, and the resulting sample was the coke sample adsorbed \(\text{Fe(NO}_3\text{)}_3\). The dried coke samples were heated under nitrogen protection until the final temperature was 1000 °C and kept constant for 60 min. The reaction equations are as follows:

\[
4\text{Fe(NO}_3\text{)}_3 \rightarrow 2\text{Fe}_2\text{O}_3 + 12\text{NO}_2 + 3\text{O}_2 
\]

\[
\text{Fe}_2\text{O}_3 + 3\text{C} \rightarrow 2\text{Fe} + 3\text{CO}_2 
\]

After decomposition, a small amount of \(\text{Fe}_2\text{O}_3\) is adsorbed on the surface of coke. Most of the \(\text{Fe}_2\text{O}_3\) particles were reduced to metallic iron at high temperature. Consequently, when it is cooled to room temperature, the adsorbed coke sample of Fe particles can be obtained. The adsorption load of Fe particles can be controlled by adjusting the concentration of \(\text{Fe(NO}_3\text{)}_3\) solution. In this experiment, five kinds of coke samples containing 0, 0.3, 1, 3, and 5% were prepared.

4.4. The Addition Method to Load Iron Particles. In addition to iron oxide loaded by the adsorption method, iron oxides can also be mixed into coal for coking. This loading mode of iron oxides is called the addition method. \(\text{Fe}_2\text{O}_3\) powder and a certain amount of water were mixed in the coal

Table 3. Proximate and Ultimate Analysis of Untreated Coal (wt %, daf)

| Analysis                        | Coal type             | Total sulfur | C   | H   | N   | O   | S   |
|--------------------------------|-----------------------|--------------|-----|-----|-----|-----|-----|
| Fixed carbon                   |                       |              | 71.48| 19.2 | 9.85| 1.34|     |
| Volatile matter                |                       |              |     |     |     |     |     |
| Ash                            |                       |              |     |     |     |     |     |
| Proximate analysis (wt %, db)  |                       |              |     |     |     |     |     |
| Ultimate analysis (wt %, daf)  |                       |              |     |     |     |     |     |

"db, dry basis; daf, dry and ash-free."
sample for coking. The water content of the coal sample was kept at 10% and the density of the pile at 0.76 t/m³, using electric heating 40 kg of coke furnace coking. The initial temperature of the furnace wall of the carbonization chamber is controlled at (700 ± 10)°C before coal loading. The total coking time is to 1050°C. The temperature of the carbonization chamber is raised from 700°C to 1050°C within 12 h for each furnace experiment, and the temperature is kept constant for 7 h. The total coking time is 19 h. Some Fe₂O₃ particles are reduced to metallic iron by C and CO gas at the high temperature. Therefore, it is the mixture of Fe³⁺ metallic iron and Fe²⁺ that exerts in changing local pore structure. The load of iron particles depends on the amount of Fe₂O₃ powder added. The reaction equations are as follows:

\[ \text{Fe}_2\text{O}_3 + 3\text{CO} \rightarrow 2\text{Fe} + 3\text{CO}_2 \]  

(5)

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Notes

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■ REFERENCES

(1) Bertling, H. Coal and coke for blast furnaces. ISIJ Int. 1999, 39, 617–624.
(2) Bhattacharyya, A.; Schenk, J.; Rantitsch, G.; Thaler, C.; Stocker, H. Effect of alkaline elements on the reactivity, strength and structural properties of blast furnace cokes. Metalurgija 2015, 54, 503–506.
(3) Feng, B.; Bhatia, S. K. Variation of the pore structure of coal chars during gasification. Carbon 2003, 41, 507–523.
(4) Guo, R.; Duan, C.; Sun, Z.; Wang, J. P.; Sun, X. W.; Liang, Y. H. Effect of pore structure and matrix reactivity on coke reactivity and post-reaction strength. Metall. Res. Technol. 2017, 114, 6.
(5) van der Velden, B.; Trouw, J.; Chaigneau, R.; van den Berg, J.; Iss, Is. Coke reactivity under simulated blast furnace conditions. In 5th Ironmaking Conference Proceedings, Iron & Steel Society: Warrendale, 1999; Vol. 58, pp. 275-285.
(6) Ishikawa, C. Y.; Kase, M.; Abe, Y.; Ono, K.; Sugata, M.; Nishi, T. Influence of post reaction strength of coke on blast furnace operation. Ironmaking Proc Metall Soc AIME 1983, 43, 357–386.
(7) Huang, J.; Guo, R.; Wang, Q.; Liu, Z.; Zhang, S.; Sun, J. Coke solution-loss degradation model with non-equimolar diffusion and changing local pore structure. Fuel 2020, 263, 116694.
(8) Grigore, M.; Sakurovs, R.; French, D.; Sahajwalla, V. Influence of mineral matter on coke reactivity with carbon dioxide. ISIJ Int. 2006, 46, 503–512.
(9) Lundgren, M.; Ökvist, L. S.; Björkman, B. Coke Reactivity under Blast Furnace Conditions and in the CSR/CRI Test. Steel Res. Int. 2009, 80, 396–401.
(10) Li, K.; Zhang, J.; Barati, M.; Khanna, R.; Liu, Z.; Zhong, J.; Ning, X.; Ren, S.; Yang, T.; Sahajwalla, V. Influence of alkaline (Na, K) vapors on carbon and mineral behavior in blast furnace cokes. Fuel 2015, 145, 202–213.
(11) Ochoa, J.; Cassanello, M. C.; Bonelli, P. R.; Cukierman, A. L. CO2 gasification of Argentinean coals: a kinetic characterization. Fuel Process. Technol. 2001, 74, 161–176.
(12) Gupta, S.; French, D.; Sakurovs, R.; Grigore, M.; Sun, H.; Cham, T.; Hilding, T.; Hallin, M.; Lindblom, B.; Sahajwalla, V. Minerals and iron-making reactions in blast furnaces. Prog. Energy Combust. Sci. 2008, 34, 155–197.
(13) Hilding, T.; Gupta, S.; Sahajwalla, V.; Björkman, B.; Wikström, J.-O. Degradation behaviour of a high CSR coke in an experimental blast furnace: Effect of carbon structure and alkali reactions. ISIJ Int. 2005, 45, 1041–1050.
(14) Ling, Q.; Zhao, H. J.; Chen, L. Y.; Xie, R. L.; Lei, Z.; Zhao, Z. G.; Cui, P. A comparison study of existence forms of Fe species in coke for solution loss reactivity of carbon. J. Iron Steel Res. Int. 2018, 25, 692–699.
(15) Bonte, L.; Sergeant, R.; Daelmans, A.; Dauwels, G.; Huyse, K. Influence of the coke and burden quality on the productivity of the blast furnace. Rev. Metall. 2005, 102, 405–410.
(16) (a) Dastidar, M. G.; Bhattacharyya, A.; Sarkar, B. K.; Dey, R.; Mitra, M. K.; Schenk, J. The effect of alkali on the reaction kinetics and strength of blast furnace coke. Fuel 2020, 268, 117388. (b) Chen, W. H.; Hsu, C. L.; Du, S. W. Thermodynamic analysis of the partial oxidation of coke oven gas for indirect reduction of iron oxides in a blast furnace. Energy 2015, 86, 758–771.
(17) Guo, R.; Duan, C.; Sun, Z.; Wang, J. P.; Sun, X. W.; Liang, Y. H. Effect of pore structure and matrix reactivity on coke reactivity and post-reaction strength. Metall. Res. Technol. 2017, 114, 6.
(18) Chang, Z. Y.; Wang, P.; Zhang, J. L.; Jiao, K. X.; Zhang, Y. Q.; Liu, Z. J. Effect of CO2 and H2O on gasification dissolution and deep reaction of coke. Int. J. Min. Met. Mater. 2018, 25, 1402–1411.
(19) Dhupe, A. P.; Gokarn, A. N.; Doraismwamy, L. K. Investigations into the compensation effect at catalytic gasification of active charcoal by carbon dioxide. Fuel 1991, 70, 839.
(20) Sun, S.; Lu, W. K. A theoretical investigation of kinetics and mechanisms of iron ore reduction in an ore/coal composite. ISIJ Int. 1999, 39, 123.
(21) Chen, Q. H.; Yang, J. H. Effect of added and adsorption minerals on coke thermal energy. J Anhui Univ. Technol. 2001, 0327–0304.