Gasification Behaviors of Ferrocoke With and Without Water Vapor

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High-reactivity coke can improve the reaction efficiency in a blast furnace, hence reducing CO$_2$ emission. Herein, traditional coke sample (QM), normal ferrocoke sample (TJ), and modified ferrocoke sample (LQ) are examined. The effect of water vapor on the gasification behaviors and structural evolution of the samples are investigated. Furthermore, the 3D structures of the coke matrix and iron particles are reconstructed by serial sectioning method. The results show that under a pure CO$_2$ atmosphere, the TJ and LQ samples start the gasification reaction earlier than the QM sample. The TJ sample shows the highest reactivity. Under CO$_2$ + H$_2$O atmosphere, the conversion rate of TJ and LQ samples is slowed. The reoxidation of the metallic iron within the ferrocoke is found for the first time during gasification and causes this phenomenon. Under experimental conditions, when water vapor appears in the atmosphere, the product layer of ferrocoke becomes more porous, and the iron particles have higher possibilities to be oxidized by CO$_2$.

1. Introduction

The blast furnace–basic oxygen furnace (BF-BOF) route currently produced 73.2% of the worldwide crude steel; 90% of the crude steel in China was produced by the BF-BOF process.[1] The BF is the major energy consumption and CO$_2$ emission unit in the BF-BOF process.[2–4] It is widely accepted that the high reactivity of coke is beneficial to improving BF’s reaction efficiency, thus reducing energy consumption and CO$_2$ emission.[5–9] The reaction efficiency was achieved by decreasing the temperature of the thermal reserve zone in BF. Here, the reactivity of coke refers to the reaction rate of coke with CO$_2$.

The reactivity of coke can be enhanced by adding alkali metals (K, Na),[10–12] alkaline earth metals (Ca),[11,14] and transition metals (Zn, Fe).[15,16] However, alkali metals are harmful elements in the blast furnace.[17] Iron is the most preferred source of catalyst. Therefore, ferrocoke, produced by adding iron-containing materials, is currently a promising type of high-reactivity coke.

Several studies tried to produce ferrocoke using local iron ore fines, iron-containing waste, and coal blends.[18–21] The addition of the iron-containing material significantly increases the reactivity of ferrocoke. Most of the iron oxide was reduced into metallic iron during coking.[18,21] 30 wt% seems to be a limit ratio for the additional amount of iron-containing material to maintain a sufficient coke strength.[19,21–23] The adverse impact on coke strength was caused by the inhibition effect of iron oxide on the cleavage of side chains of the coal structure; the amount of fluid phase decreased during coking.[24] Binder, therefore, becomes a necessity to increase the coke strength. Phenolic resins, petroleum pitch, and coal tar pitch were regarded as good choices for producing ferrocoke.[25–27]

More attention has been paid to the injection of hydrogen-containing fuel to BF to further reduce CO$_2$ emissions. Therefore, the water vapor content in BF increases sharply. Under high temperature, the gasification reaction of coke in a water vapor atmosphere is more intense than that in a CO$_2$ atmosphere.[28–30] The water vapor can enhance the internal diffusion and interface reaction during coke gasification. However, the influence of water vapor on the gasification of ferrocoke is still unclear.

Our previous work examined the influences of the type variety, addition amount, and particle size of iron ore powders on the pyrolysis behavior and strength of coal–iron ore briquettes.[21,23,31] Several binders were tested to increase the coke strength. Meanwhile, the gasification reaction characteristics under pure
CO₂ atmosphere were analyzed. Based on the previous work, an optimum condition was obtained. The current work investigated the influence of water vapor on the gasification reaction of the ferrocoke. The reoxidation of metallic iron within the ferrocoke during the gasification was found for the first time. Furthermore, the thermodynamic calculation was conducted based on the experimental conditions using FactSage 8.0. The structural evolutions of the coke matrix and iron particles were investigated using interrupted gasification experiments. 3D structures of the coke matrix and iron particles were reconstructed via a serial sectioning method, and a gasification mechanism of ferrocoke was proposed.

2. Experimental Section

2.1. Experimental Materials

The pulverized coal and iron ore used in this study were gas coal (GQ) from the Guanqiao district and a typical oolitic type hematite iron ore (EX) from the western Hubei province in China. One type of coal tar pitch with a coking value of 56% was used as a binder to improve the strength of ferrocoke. The proximate analysis and ultimate analysis of the gas coal and coal tar pitch were carried out based on the National Standards GB/T212-2008 and GB/T31391-2015. The result is listed in Table 1. The ash composition of the GQ is shown in Table 2. The chemical composition of the EX is listed in Table 3.

2.2. Sample Preparation

The GQ coal with a particle size of <1 mm and the EX ore with a particle size between 0.2 and 0.5 mm were obtained by crushing and sieving. Then, the EX ore particles were dried in a drying oven under 40 °C for 10 h. In a higher drying temperature, for example 100 °C, the EX ore particles would spontaneously be broken into smaller fines. Therefore, the 40 °C drying temperature was chosen.

Three types of coke samples were prepared using different ratios of the raw materials, as shown in Table 4: 1) traditional coke sample (QM); 2) normal ferrocoke sample (TJ), and 3) modified ferrocoke sample (LQ). The preparation of these three samples followed the same procedure, as shown in Figure 1. 10 g of the raw material or material mixture were put into a small cylindrical graphite crucible (Φ20 × 60 mm). A stainless steel column with a diameter of 20 mm and a height of 70 mm was placed above the raw materials. The stainless steel column provided a pressure of about 0.031 atm. The CO₂ was supposed to pick up all the saturated CO₂. Then it was further heated up to 1100 °C at a heating rate of 5 °C min⁻¹. The furnace was kept for four hours at 1100 °C to realize deep pyrolysis. 1 L min⁻¹ of N₂ was introduced as a protective gas during the whole carbonization process and cooling of the sample until the temperature dropped to 170 °C. The obtained samples were in cylinder shapes with diameters around 19 mm. The length of different types of coke samples was slightly different.

2.3. Research Method

2.3.1. Gasification Reaction

The gasification reaction was conducted in a high-temperature vertical furnace, as shown in Figure 2. The experimental temperatures were selected as 1000, 1100, and 1200 °C, respectively. Two types of the experimental atmosphere were used: 1) pure dry CO₂ and 2) a mixed gas of CO₂ and water vapor. The supply of the water vapor was conducted by a gas cylinder in a water bath at 25 °C. When water vapor was injected, an insulation jacket was used to prevent the condensation of water vapor. At room temperature (25 °C), the saturation pressure of water was 0.031 atm. The CO₂ was supposed to pick up all the saturated water vapor. Therefore, the water content in the mixing gas should be around 3.1% in volume ratio. The gas flow rates for

### Table 1. Proximate analysis and ultimate analysis of the GQ coal and coal tar pitch (wt%).

| Sample           | Fixed carbon | Volatile matter | Moisture | Ash  | C    | H    | O    | N    | S    |
|------------------|--------------|-----------------|----------|------|------|------|------|------|------|
| GQ               | 57.52        | 31.58           | 2.63     | 8.27 | 69.78 | 8.07 | 10.33 | 0.73 | 0.19 |
| Coal tar pitch   | 51.64        | 46.07           | 1.03     | 1.26 | 91.97 | 3.92 | 2.54  | 0.74 | 0.70 |

### Table 2. Ash composition analysis of the GQ coal (wt%).

| Component     | GQ          | EX          | Coal tar pitch |
|---------------|-------------|-------------|----------------|
| SiO₂          | 67.53       |             |                |
| Al₂O₃         | 21.97       |             |                |
| CaO           | 3.02        |             |                |
| K₂O           | 1.76        |             |                |
| Fe₂O₃         | 1.57        |             |                |
| TiO₂          | 1.47        |             |                |
| SO₃           | 0.91        |             |                |
| Na₂O          | 0.75        |             |                |
| MgO           | 0.60        |             |                |
| MnO           | 0.02        |             |                |

### Table 3. The chemical composition of the EX (wt%).

| Component     | Fe₄O₇ | FeO  | SiO₂  | CaO  | Al₂O₃ | MgO  | P    | S    | LOI\(^{a}\) |
|---------------|-------|------|-------|------|-------|------|------|------|-------------|
| Sample        |       |      |       |      |       |      |      |      |             |
| Gas coal coke (QM) | 55.15 | 0.82 | 11.59 | 0.19 | 4.55  | 0.34 | 0.134| 0.022| 0.63        |
| Ferro-coke (TJ) | 70    | 30   | 30    | 0    | 30    | 0    | 10   | 0    | 0           |
| Modified ferro-coke (LQ) | 60| 30   | 10    |      |      |      |      |      |             |

\(^{a}\)LOI: Loss on ignition.
pure dry CO$_2$ were 1, 2, 3, 4, and 5 L min$^{-1}$. The gas flow rate for the mixed gas of CO$_2$ and water vapor was 5 L min$^{-1}$.

To avoid the impact of the sample shape on the gasification reaction, all the samples were ground into the same length. The size of all samples was approximately $\Phi$19 $\times$ 15 mm. Due to the different densities of the coke samples, the weights of each QM sample, TJ sample, and LQ sample were about 3.0 $\pm$ 0.05 g, 3.1 $\pm$ 0.05 g, and 3.05 $\pm$ 0.05 g, respectively. When the furnace temperature reached the setting value, the reaction gas was introduced from the bottom into the reactor. After a 10 min temperature and gas equilibrium period, the sample was put into the reaction zone by a customized Al$_2$O$_3$ crucible with holes on the bottom. The crucible was hung by a stainless wire and fixed to the weighting system. When no weight loss occurred, the sample was pulled out of the reactor and quenched by N$_2$ gas. The conversion was defined as Equation (1).

\[
\text{Conversion} = R = \frac{m_0 - m_t}{m_0 - m_\infty}
\]

(1)

where $m_0$ is the initial weight of the ferro-coke, g; $m_t$ is the weight of the ferrocoke during the experiment, g; and $m_\infty$ is the final weight of the sample after the experiment, g.
2.3.2. 3D Reconstruction Method

The pore system in the ferrocoke was a network 3D structure. It is difficult to characterize the details, for example, the connections between the pores and the distributions of the pores in 3D space, using 2D images. The serial sectioning method was used to reconstruct the 3D pore structures of the ferrocoke and analyze the pores before and after gasification reaction comprehensively and intuitively. Moreover, the structures of the coke matrix and the iron particles were reconstructed. The 3D reconstruction process is shown in Figure 3 and was also introduced in our previous studies.[32–34] The principle of the serial sectioning method was to obtain 2D images from adjacent layers of the sample. With image processing, the 2D images could be constructed as a 3D image.

Sixteen images from the same layer were merged as one 2D image to obtain a larger observation view of the selected area. Figure 4 shows an example of the merging process. The red dotted areas were the overlapping part from the adjacent fields of images. Principally, the overlapped areas were merged during the process. The colors of the coke matrix structure were presented differently, which may influence the following segmentation process. Therefore, the images were further processed into binary grayscale images by Image J software before reconstruction, as shown in Figure 5.

Figure 3. Steps for establishing a 3D model of the ferrocoke microstructure.

Figure 4. Splicing of microscopic images of ferrocoke.

3. Results and Discussion

3.1. The Influence of the Gas Flow Rate

The previous study[24] showed that external diffusion could be eliminated with the increasing gas flow rates. Figure 6 shows the influence of CO₂ flow rate on the gasification reaction of the QM sample at 1100 °C. The starting and ending points of the gasification reaction were defined when the conversion reached 5% and 95%, respectively. As shown in Figure 6a, with the increase of CO₂ flow rate, the conversion curve gradually shifted to the left. The starting points and the ending points of the gasification reaction were in the range of 325–539 s and 5730–9779 s at the flow rate from 1 to 5 L min⁻¹. From Figure 6b, the conversion rate was higher in the initial reaction stage in the condition with a higher CO₂ flow rate. It should be noted that the gasification kinetics showed a neglectable
difference when the CO2 flow rate increased from 4 to 5 L min\(^{-1}\). It can be concluded that when the gas flow rate reached 5 L min\(^{-1}\), the influence of mass transfer within the gas film can be eliminated. Therefore, the CO2 flow rate was set as 5 L min\(^{-1}\) in the subsequent experiments.

3.2. The Influence of Reaction Temperature

Figure 7 shows the comparison of the reaction progress of the QM sample, TJ sample, and LQ sample at different temperatures under the CO2 atmosphere. As shown, a higher reaction temperature increased the gasification reaction rate significantly. From Figure 7d–f, the QM sample presented the lowest maximum conversion rates at different temperatures in the range of \(1.5 \times 10^{-4} - 3.2 \times 10^{-4}\) s\(^{-1}\), while TJ showed much higher maximum conversion rates in the range of \(3.5 \times 10^{-4} - 7.1 \times 10^{-4}\) s\(^{-1}\). Compared with the TJ sample, the LQ sample showed slightly lower maximum conversion rates in the range of \(3.0 \times 10^{-4} - 6.2 \times 10^{-4}\) s\(^{-1}\). The starting and ending points of the gasification reaction are shown in Figure 8. The reaction started and ended earlier at a higher reaction temperature.

The TJ and LQ samples started the gasification reaction earlier than the QM sample, especially at high temperatures. The starting point was shortened from 325 s (QM) to 165 s (TJ) and 206 s (LQ) at 1100 °C and from 238 s (QM) to 126 s (TJ, LQ) at 1200 °C.

It can be concluded that, under pure CO2 atmosphere, the TJ sample has the highest reactivity, followed by the LQ sample. The result is consistent with the previous studies.[22,27] The addition of coal tar pitch increased the cold drum strength but decreased the reactivity compared with normal ferrocoke. It was explained that the coal tar pitch enhanced the bonding of the coal and iron ore particles, resulting in lower porosity.[27]

3.3. The Influence of the Reaction Atmosphere on the Gasification of Ferrocoke

Figure 9 shows the conversion curves of the ferrocoke samples at 1000, 1100, and 1200 °C under the CO2 and the CO2 + H2O atmosphere. It can be seen that in each condition, TJ samples showed the highest conversion rate, followed by the LQ sample. Wang et al.[28] Zhang et al.[35] and Lan et al.[30] studied the influence of water vapor using industrial metallurgical coke. It was
found that the chemisorption of H₂O on the coke surface was more potent than that of CO₂. Due to the smaller size of the H₂O molecule, the diffusion rate was faster. The enhancement effect was explained that the water vapor reacting with the coke more frequently, and a large number of small pores and micro-cracks were generated on the surface of the coke. Furthermore, CO₂ diffused into the coke interior easier through the pores and micro-cracks caused by H₂O.

However, the addition of water vapor showed a negative effect on the conversion rates of the ferrocoke samples in the present study. Unexpectedly, the conversion rates of the TJ and the LQ samples were lower in the CO₂ + H₂O atmosphere than that in the pure CO₂ conditions. This can be explained by the reoxidation of metallic iron in the ferrocoke samples. The metallic iron picked the oxygen from water vapor and CO₂; thus, the conversion (or so-called apparent conversion) rate was decreased. The reactions (2) and (3) may occur during the reaction with CO₂ and H₂O.[36,37]

\[
\begin{align*}
\text{Fe} + \text{CO}_2(g) &= \text{FeO} + \text{CO} \quad (2) \\
\text{Fe} + \text{H}_2\text{O}(g) &= \text{FeO} + \text{H}_2 \\
\end{align*}
\]

To confirm the reoxidation of the metallic iron, the raw and reacted TJ samples were examined by scanning electron microscope (SEM)–energy-dispersive X-Ray spectrometer (EDS) analysis. Figure 10 shows the SEM–EDS analysis of the raw TJ sample and the TJ sample after 20 min reaction under the CO₂ + H₂O atmosphere at 1100 °C. As shown in Figure 10a, the bright phases in the raw TJ sample were metallic iron. After the reaction, as shown in Figure 10b, the bright phases became gray. After eliminating O that bonded with gangue elements (Si, Mg, Al), the element ratios between Fe and O from P5 and P6 were close to 1, representing the FeO phase. The ratio from P7 was close to 1.5, representing Fe₂O₃. The detailed oxidation of Fe was also calculated from a thermodynamic point of view in the following section.

3.4. Thermodynamic Calculation

Based on the experimental conditions, FactSage 8.0 was used to study the reoxidation of metallic iron during the reaction.
The ferrocoke sample was considered as a mixture of 2.1 g of C and 0.9 g of Fe. Two cases were calculated, and the detailed input parameters are listed in Table 5. The output gas and solid compositions were calculated by the FactPS, FSoxid and FSlead databases of the Equilib module in FactSage 8.0. The results are shown in Figure 11 and 12. In case 1, the CO2 gas flow rate was 0.2232 mol min⁻¹. In case 2, the CO2 and H2O gas flow rates were 0.2165 and 0.007 mol min⁻¹, respectively.

From Figure 11, under pure CO2 conditions at 1100 °C, the reaction can be divided into four stages. In stage I, C reacted with Fe and formed FeC. Meanwhile, C reacted with CO2 and formed CO. When C was totally consumed, in stage II, the decomposition of FeC occurred. Stage III occurred when FeC was totally decomposed, that is, the oxidation of Fe started. At stage III, CO2 reacted with Fe to form both FeO and Fe₂O₃ in parallel, where FeO was the dominant product. When Fe was totally consumed (stage IV), the FeO started to react with CO2 and form Fe₂O₃. The general reaction at the start point of stage IV was given quantitatively in Figure 11c.

Figure 12 shows the result under CO2 + H2O conditions at 1100 °C. Similar to the result that under pure CO2 conditions,
the reaction can be divided into four stages. In stage I, C reacted with Fe and formed FeC. Meanwhile, C reacted with CO\textsubscript{2} and H\textsubscript{2}O to form CO and H\textsubscript{2}. When C was totally consumed, in stage II, the decomposition of FeC occurred. Compared with that in pure CO\textsubscript{2} conditions, in stage III, the oxidation of Fe was caused by both CO\textsubscript{2} and H\textsubscript{2}O. When Fe was totally consumed (stage IV), the FeO started to react with CO\textsubscript{2} and form Fe\textsubscript{2}O\textsubscript{3}. It should be pointed out that the water–gas shift reaction (CO \textsubscript{2} + H\textsubscript{2}O = CO + H\textsubscript{2}) did not happen in this case due to the low content of H\textsubscript{2}O. On the contrary, due to the excess CO\textsubscript{2}, the amount of H\textsubscript{2} and the consumed H\textsubscript{2}O (\Delta H\textsubscript{2}O) started to decrease (stage IV). FeO acted as a catalyst, H\textsubscript{2} reacted with CO\textsubscript{2} and formed H\textsubscript{2}O and CO. The general reaction at the start point of stage IV is given quantitatively in Figure 12c.

In general, from the thermodynamic point of view, the two cases did not show big difference. However, as discussed in Section 3.3, the addition of water vapor should enhance the gasification reaction of coke. The water vapor also accelerated the reoxidation of the metallic iron in the TJ and LQ samples. This phenomenon was explained by microstructure analysis in the following sections.

3.5. Evolution of the Microstructure During the Gasification Reaction

The structural evolution of the samples during the gasification reaction at 1100 °C under pure CO\textsubscript{2} conditions was analyzed. The reacted samples with different reaction times presented different sizes. For a comparable analysis, the positions close to the center of the samples were selected as interesting observation areas. The surface morphologies of the QM, TJ, and LQ samples with different duration reaction times are shown in Figure 13a–i. For the QM sample, as shown in Figure 13a–c, after 20 min, the ash and residual carbon matrix appeared on the surface. With increasing the reaction time, the remaining carbon matrix showed a porous flake structure. As shown in Figure 13d–f, a few spherical iron particles could be observed on the surface of the TJ sample. The amount of the iron particles increased with the reaction time. Because the surrounding carbon matrix was consumed. The surfaces of the iron particles in the TJ sample with 20 min reaction time were rough. After 40 min, the iron particles exhibited a smooth surface with a metallic luster. However, after 60 min, the surface of the iron particles was covered by ash. Figure 13j,k show the cross-section images of the unpolished TJ samples after 40 min and 60 min reactions. The iron particles became more extensive, and the carbon matrix became more porous with the reaction time. The iron particles close to the sample edges seemed to be melted, which was caused by the diffusion of the iron. The longitudinal section image of the TJ sample after 20 min reaction is shown in Figure 13L, where a clear shrinking core can be observed. For the LQ sample, the morphology was similar to that of the TJ sample. The formed iron particles were bigger than the original iron ore powders in both TJ and LQ samples. It means that during the gasification reaction,
Figure 12. The output phase amount and relevant reactions under CO$_2$ + H$_2$O conditions at 1100 °C: a) solid-phase compositions and b) gas-phase compositions. ΔH$_2$O is the consumed H$_2$O during the reactions; c) relevant reactions. The ΔH$_2$O and H$_2$ lines in (b) are overlapped.

Figure 13. Microstructures of different reacted samples under pure CO$_2$ conditions: a–i) unpolished surface morphologies of the reacted samples with different reaction times; j,k) unpolished cross-section images after 40 and 60 min reaction; and l) polished longitudinal section image of TJ sample after 20 min reaction.
the formed iron particles could diffuse through the pores of the coke. When the small iron particles met, a larger iron ore particle was formed. It should be pointed out that the iron particles were partly oxidized into FeO or Fe₂O₃ by CO₂ and H₂O. Compared with the TJ sample, fewer iron particles in the LQ sample can be observed. This can be explained by the lower gasification reaction rate of the LQ sample. The consumption of the carbon matrix was slower, which was not favorable to the movement of the iron particles.

To further analyze the structural evolution of carbon matrix and iron particles, the 3D structures of the TJ sample were reconstructed, as shown in Figure 14. Figure 14a–c shows the 2D polished cross-section images of the TJ sample after 10, 20, and 30 min reaction. The carbon matrix and the iron particles in the green and red box areas were reconstructed into 3D versions, which are shown in Figure 14d–i, respectively. It was observed that after 10 min, the carbon structure was porous but still with thick pore walls. When reaction time increased to 20 min, more open pores were observed, and the pore walls became thinner. After 30 min, the pore wall collapsed due to the gasification reaction, and bigger pores were formed. The metallic iron was intertwined with the original impurities of the iron ore powder. Meanwhile, the iron particles picked up the remaining ash of the coke during its movement and growth. These impurities inside the iron particles were not visible in the 2D images. It can be concluded that during the gasification, the iron particles became larger and more compact.

As discussed in Section 3.4, at the beginning of the gasification, FeC is to be formed. Theoretically, the oxidation of Fe only occurs when C is totally consumed. In the present study, the iron particles were surrounded by the carbon matrix. It was easier for CO₂ to react with the nearby carbon before reaching the iron

![Figure 14](image-url). The evolution of the 3D structures of the carbon matrix and iron ore particles during the gasification reaction under pure CO₂ conditions: a–c) 2D images after 10, 20, and 30 min; d–f) 3D structures of carbon matrix after 10, 20, and 30 min; g–i) 3D structures of iron particles after 10, 20, and 30 min; The red phase is the metallic iron and the blue phase is the impurity phase. The two images in (d–f) are the same structures in a different direction. The two images in (g–i) are the same structures with single and double phases.
particles. Based on previous study,[27] the decomposition of the ketone group was the limiting step during the carbon gasification with CO₂. The iron atom could reduce the reaction energy of the decomposition of the ketone group. Under pure CO₂ conditions, iron mainly played a role as a catalyst. However, the reaction mechanism in the CO₂ + H₂O atmosphere is different and shown in Figure 15. When the water vapor appeared in the atmosphere, it diffused faster than CO₂ due to its smaller molecular size. The product layer became more porous, which was more conducive to the further diffusion of CO₂. Hence, the carbon consumption rate became higher. Therefore, the iron particles had higher possibilities to react with the CO₂.

4. Conclusion

Based on the present experiment results, thermodynamic calculation, and structure investigation, the influence of water vapor on the gasification reaction of ferrocoke is as follows. 1) The influence of external diffusion in the gas film could be eliminated when the gas flow rate reached 5 L min⁻¹. A higher reaction temperature increased the gasification reaction rate significantly. Under a pure CO₂ atmosphere, the TJ and the LQ samples started the gasification reaction earlier than the QM sample, especially at high temperatures. The starting point was shortened from 325 s (QM) to 165 s (TJ) and 206 s (LQ) at 1100 °C and from 238 s (QM) to 126 s (TJ, LQ) at 1200 °C. 2) Under the CO₂ + H₂O atmosphere, the conversion rates of TJ and LQ samples were lower than that in pure CO₂ conditions. This was caused by the reoxidation of the metallic iron in the samples. From a thermodynamic point of view, the reaction can be divided into four stages. At the beginning of the gasification, FeC was to be formed. The oxidation of Fe occurs when C is totally consumed. Most Fe can be oxidized into FeO in experimental conditions. The metallic iron picked the oxygen from CO₂ and water vapor. Thus, the conversion rate decreased. 3) A few spherical iron particles could be observed on the surface of the ferrocoke after the gasification reaction. The iron particles became more extensive than the original iron ore powders, and the carbon matrix showed more porous with the reaction time. Under pure CO₂ conditions, the iron mainly acted as a catalyst. When water vapor appeared in the atmosphere, the product layer became more porous, which was more conducive to the further diffusion of CO₂. Therefore, the iron particles had higher possibilities to react with the CO₂. 4) It is suggested that when the water vapor content is high in a blast furnace, such as in a hydrogen blast furnace, the addition of ferrocoke should be lower. In the fabrication of ferro-cake, the addition of iron ore should be also lower than usual to keep from oxidation.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

ferrocoke, gasification reactions, structural evolution, water vapor

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