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SCIENTIFIC PAPER

UDC 553.64:544:66

## EFFECT OF DIFFERENT CARBON SOURCES ON VACUUM CARBOTHERMAL REDUCTION OF LOW-GRADE PHOSPHORUS ORE

### Article Highlights

- The pulverized coal and coke could reduce the melting initiation temperature
- The maximum reduction effect was obtained using graphite in the thermodynamic calculation results
- Existence of crystal water and volatiles promoted the reaction
- The optimum reduction agent in the experiment was graphite

### Abstract

*In this study, the effect of different carbon sources on the carbothermal reduction of low-grade phosphate ore were examined using FactSage 7.2 calculations and vacuum reduction experiments. The thermodynamic calculations showed that the trend of the effect for three types of reducing agents was generally consistent under 1 Pa pressure and 14% carbon dosage. The reduction effect was maximum when graphite was used as the reducing agent, and a maximum mass of P was obtained at 1250 °C. The vacuum experiment results showed that the reduction and volatilization ratios of phosphate rock increased with temperature for different carbon sources. Maximum reduction ratio was obtained using graphite in the temperature range 1250–1300 °C. The reduction effect of pulverized coal was optimal at 1350 °C, when SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and MgO in the pulverized coal ash were exposed to form low-melting eutectics with CaO due to the increased degree of reaction, and the heat and mass transfer rates were increased. At this time, a maximum reduction ratio of 51.77% of the sample and a maximum volatilization ratio of 82.44% of P were achieved. Considering the cost-effectiveness, pulverized coal was the optimum carbon source for the treatment of low-grade phosphate rock using vacuum carbothermal reduction.*

*Keywords: vacuum carbothermal reduction, FactSage, carbon sources, low-grade phosphate ore.*

Phosphorus is a non-renewable and irreplaceable resource that is primarily used to prepare phosphate fertilizer, and it also plays an important role in the fields of food, medicine, etc. [1]. Phosphorus has high reactivity and is primarily found in nature in the form of oxides [2]. Resources of phosphorus in China are abundant, but are of low grade; enriched ores with grades above 30% accounted for only 7% of the total P ores, while collophane accounted for ~80% of the

total. Moreover, the average grade of phosphate ore is only 16.85% [3]. Phosphate rock has been continuously exploited; therefore, high-grade phosphate ore has gradually depleted, making the development of low-grade phosphate ore as an important source necessary.

At present, there are primarily two methods to produce phosphoric acid using phosphate ore: wet phosphoric acid method and thermal phosphoric acid method [4]. In the thermal process, the grade of phosphate ore must be higher than 28%; volatile yellow phosphorus is sprayed into the bottom of a sedimentation tank through condensed water in a cooling tower, and is finally refined using a refining pot. The yellow phosphorus is oxidized and hydrated to obtain

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 Paper received: 19 February, 2021  
 Paper revised and accepted: 20 April, 2021

<https://doi.org/10.2298/CICEQ210219013H>

the final product. The phosphoric acid produced using this method is of high quality and produces low environmental pollution. However, it is a time-consuming and high energy-consuming process, which consumes 14,000 kWh of electricity to produce one ton of yellow phosphorus [5,6]. In the wet process, a strong acid is used to leach the phosphate rock [7]. However, the impurity removal process of subsequent products is complicated. Phosphogypsum, a byproduct, has caused severe wastage of resources and heavy metal pollution [8,9]. Some researchers have proposed a kiln process based on the thermal method for phosphoric acid synthesis, in which low-grade ores can be directly treated. In this process, the reduction and oxidation reactions are carried out in the same reactor [10], thus enabling complete utilization of the combustion heat during the reaction process and significantly reducing energy consumption. However, owing to uneven temperature distribution in the kiln, the raw materials form loops in the kiln and cause problems, such as the inability to continuously operate the equipment, resulting in a poor phosphate rock reduction effect [11,12].

As the resource of high-grade phosphate rock decreased annually, comprehensive utilization of low-grade phosphorus rock gradually gained attention from researchers. Based on the smelting reduction process for the production of iron, lead, zinc, *etc.*, Guo *et al.* [13,14] used pulverized coal instead of coke for the smelting reduction of phosphorus ore, which involves placing the phosphate rock in the reactor and then spraying pulverized coal and oxygen for reduction. The oxidation and reduction reactions were performed in the same reactor, which could effectively utilize the combustion heat in the reaction process. The coal-oxygen-ore injection could accelerate the molten mass transfer, increase the reaction ratio and reduction ratio, and reduce energy consumption. Based on the melting reaction, Hu *et al.* [15] proceeded from the reactive state to make the reactants form a partial molten liquid phase during the reaction process, which could effectively reduce the experimental temperature and energy consumption. The factors influencing the reduction ratio of phosphate rock were investigated during the smelting reduction process, and the optimal conditions for smelting reduction of phosphate rock was as follows: graphite was used as the reducing agent, reaction temperature was 1450 °C, reaction time was 60 min, the

silicon-to-lime mole ratio was 2.4, and the carbon excess coefficient was 1.5. The reduction ratios of phosphate ore can reach 96%. In recent years, NiSO<sub>4</sub> has shown good catalytic activity for metal reduction, and experiments have proved that NiSO<sub>4</sub> can strengthen the activity of reducing agents [16]. Cao *et al.* [17] added aqueous NiSO<sub>4</sub> to coke, which was then dried and crushed, mixed with the raw materials, and pelletized into the reactor for roasting. When the reduction temperature was 1300 °C, reaction time was 60 min, silicon-to-lime mole ratio was 1.1, and the excess coefficient of graphite power was 1.1, the reduction ratio of phosphate rock increased from 75.56 to 90.68%. Some researchers, referring to the application of vacuum reduction in metallurgy, have proposed a new process for treating low-grade phosphate rock using vacuum carbothermic reduction. The experiments proved that vacuum treatment was effective. Li *et al.* [18-20] studied the thermodynamic behavior and reduction kinetics for the carbothermal reduction of calcium fluorophosphate under vacuum, and concluded that the reduction mechanism of Ca<sub>5</sub>(PO<sub>4</sub>)<sub>3</sub>F under vacuum was as follows: Ca<sub>5</sub>(PO<sub>4</sub>)<sub>3</sub>F preferentially reacted with SiO<sub>2</sub>, defluorinated, and formed Ca<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub>; Ca<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub> then reacted with C to produce CaO, which combined with SiO<sub>2</sub> to form CaSiO<sub>3</sub>; F was finally discharged from the system in the form of SiF<sub>4</sub>(g). Huang *et al.* [21-23] studied the factors influencing the reduction ratio of phosphate rock, such as carbon dosage, temperature, and pressure, by combining FactSage theoretical calculations and experiments; the optimum reaction conditions were as follows: pressure = 10 Pa, carbon dosage = 14%, and temperature, 1250-1300 °C. However, the reduction behavior of phosphate rock under different carbon sources is explored, and in terms of economic cost, it provides data support for comprehensive utilization of low-grade phosphate ore. Based on this, the influence of different carbon sources on the vacuum carbothermal reduction of phosphate rock under vacuum conditions was investigated.

## EXPERIMENTAL

### Materials

The phosphate rock was obtained from Yunnan, and the chemical composition of the phosphate ore is shown in Table 1.

Table 1. Chemical analysis of raw material (wt. %)

Component	CaO	P <sub>2</sub> O <sub>5</sub>	F	SiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	K <sub>2</sub> O	Al <sub>2</sub> O <sub>3</sub>	Na <sub>2</sub> O
Content	49	29	1.4	5	2	1.7	1.1	0.3	0.1

The X-ray diffraction (XRD) pattern of the raw ore (Figure 1) showed that P primarily exists in the form of  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  in the raw ore and Si primarily exists in the form of  $\text{SiO}_2$ .

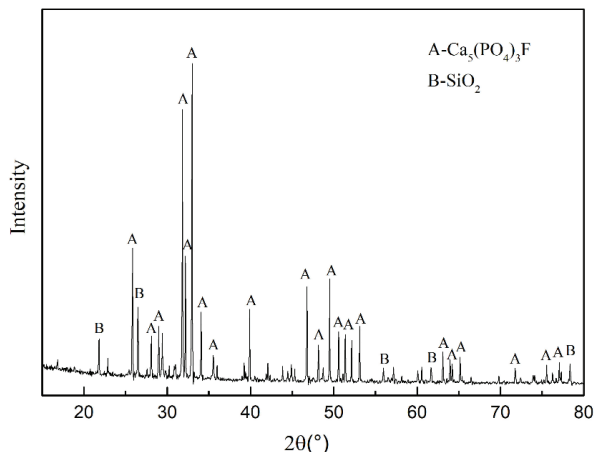


Figure 1. XRD spectrum of the phosphorite ore.

The chemical compositions of the reducing agents (graphite, coke and pulverized coal) are shown in Table 2, and the fixed carbon contents were 99, 83.66 and 62.75%, respectively. The particle size of the reducing agents was reduced to 200 mesh by

grinding, and the binder (0.4%) used was methylcellulose M20.

The reduction experiments were performed in an MTLQ-TG-40 vacuum vertical tube furnace; the structure is shown in Figure 2. High-purity graphite was used as the heater; the maximum operating temperature was 2000 °C and the maximum vacuum was  $6.67 \times 10^{-3}$  Pa.

### Method

According to previous studies [22], the carbon dosage used in the reduction experiments was maintained at 14%, and the experiments were conducted under vacuum (1 Pa). The graphite powder, binder, and water were thoroughly mixed and formed into pellets, and the green pellets were then placed in a vacuum carbon tube furnace. The experimental design scheme is shown in Table 3. The heating rate was 6 °C/min. When the temperature reached the setting temperature for 60 min, heating was stopped, and the samples were then cooled to room temperature through water circulation. The cooling rate was 13.3 °C/min when the temperature was higher than 1000 °C, 6.15 °C/min when the temperature was 600–1000 °C, and 3 °C/min when it was below 600 °C. After cooling the pellets to room temperature, they were removed and weighed for further phase ana-

Table 2. Chemical composition of different carbon sources

Source	FC	S	P	Fe	Var	Mar	Ash	Ash						
								$\text{Fe}_2\text{O}_3$	CaO	$\text{Al}_2\text{O}_3$	$\text{SO}_3$	MgO	$\text{SiO}_2$	$\text{Na}_2\text{O}$
Graphite	>99	-	-	0.045	0.5	-	0.24	-	-	-	-	-	-	-
Coke	83.99	0.65	0.12	-	2.22	-	14.12	8.91	6.01	22.26	2.16	-	47.79	-
Pulverized coal	62.75	-	-	-	8.89	15.4	12.96	17.05	29.07	14.81	8.84	1.49	22.22	1.34

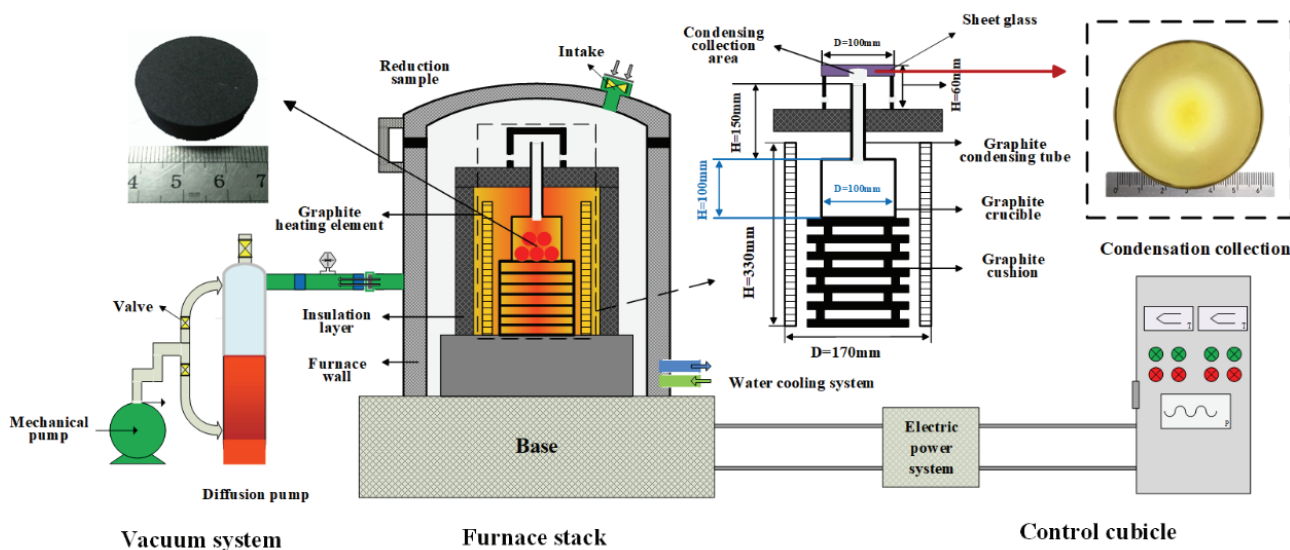


Figure 2. Schematic diagram of vacuum carbon tube furnace.

lysis. The reduction and volatilization ratios of phosphorus were defined as follows:

$$\theta = 100 \frac{m_1 - m_2 - m_3 + (M - M_0)}{m_1 - m_3} \quad (1)$$

$$\eta = 100 \frac{M - M_0}{M} \quad (2)$$

where  $\theta$  is the phosphorus reduction ratio (%);  $\eta$  is the volatilization rate of phosphorus (%);  $m_1$  is mass of samples before heating (g);  $m_2$  is mass of samples after heating (g);  $m_3$  is mass of binder (g);  $M$  is mass of P in ore samples before reduction (g);  $M_0$  is mass of P in ore sample after reduction (g).

## RESULTS AND DISCUSSION

### Theoretical calculations

When the system pressure was 1 Pa, carbon dosage was 14%, and coke, graphite, and pulverized coal were used as reducing reagents, the product composition and volatilization ratio of P were calculated

using FactSage 7.2 software with a module of equilibrium under different conditions.

The results are shown in Figure 3. At 1150 °C, P appears in the gas phase under different conditions. The tendency of P volatilization for three types of reducing agents remained nearly constant with increasing temperature; it increases initially and then decreases, and the maximum volatilization ratio was obtained at 1250 °C. The volatilization ratio of P decreased with increasing temperature from 1250 to 1450 °C. The maximum volatilization effect of P was obtained using graphite under different temperature conditions, followed by that of using pulverized coal. Moreover, the volatilization effect of P was the lowest when coke was used as the reducing reagent. At 1200 °C,  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  reacted with  $\text{SiO}_2$  and decomposed by itself to produce  $\text{Ca}_3(\text{PO}_4)_2$ , but the mass of CO,  $\text{P}_2$  and CaO did not change under different conditions. At 1300 °C, P was oxidized partially, and small amounts of PO began to appear in the gas phase.

The theoretical relationship between the masses of CaO,  $\text{P}_2\text{O}_5$  and liquid slag and temperature is

Table 3. Experimental design scheme

Carbon dosage	Holding time	Carbon source			Temperature, °C		
14%	60 min	Coke	Graphite	Pulverized coal	1250	1300	1350

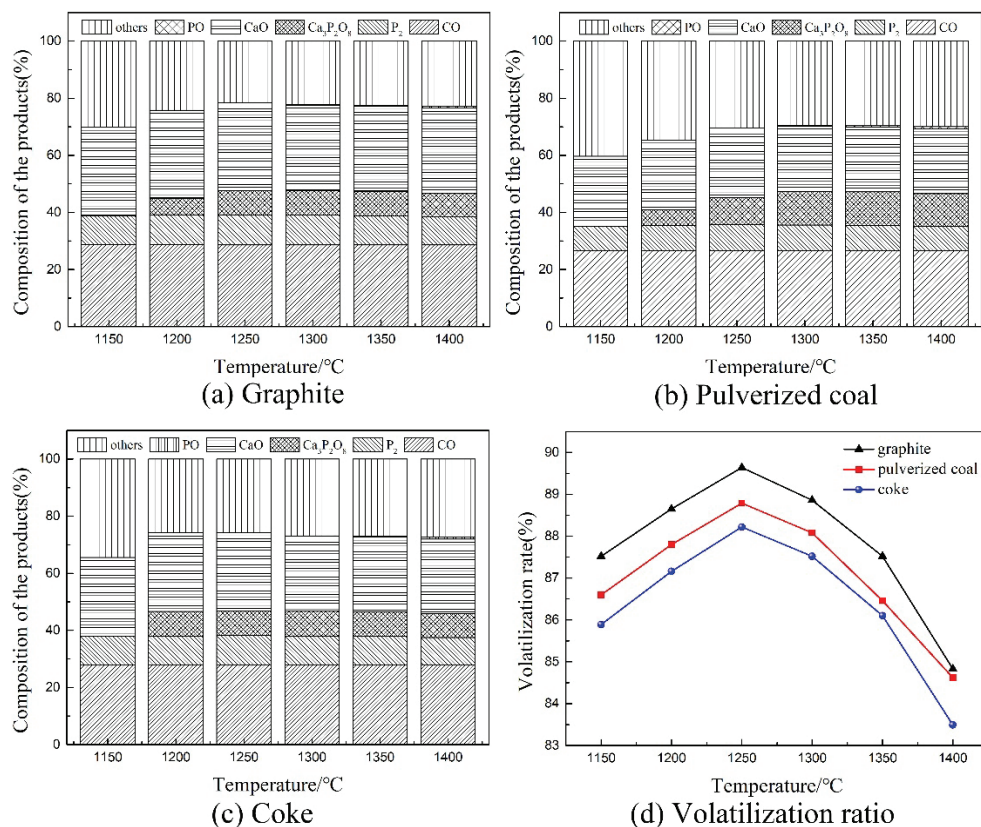


Figure 3. Composition diagram of products under different carbon sources.

shown in Figure 4. When graphite was used as the reducing reagent, a liquid phase appeared at 1300 °C, which was the melting initiation temperature. The masses of CaO and P<sub>2</sub>O<sub>5</sub>, as well as the amount of the liquid phase, increased with increasing temperature. When pulverized coal was used as the reducing agent, the liquid phase appeared at a temperature of 900 °C, which was the melting initiation temperature. The masses of CaO and P<sub>2</sub>O<sub>5</sub>, as well as the amount of liquid phase, increased slowly with increasing temperature. It changed significantly above 1200 °C, and the maximum masses of CaO, P<sub>2</sub>O<sub>5</sub> and liquid slag were 50.9, 32.37 and 96.7 g, respectively. When coke was used as the reducing agent, the liquid phase appeared at 1100 °C, which was the melting initiation temperature. As the temperature increased, the maximum mass of the product was obtained at 1800 °C. It can be seen from the figure that coke and pulverized coal, as reducing reagents, can effectively reduce the reaction initiation and reaction termination temperatures; the reason for this is that coke and pulverized coal contained crystal water and volatile compounds. Pulverized coal exhibited the most optimal effect.

## Experimental results

### *Influence of different carbon sources on the reduction ratio of samples*

The experimental relationship between temperature and reduction ratio of the reduced samples for different carbon sources is shown in Figure 5. The samples were maintained at 1250, 1300 and 1350 °C for 60 min. The reduction ratios of all the samples for the different carbon sources increased with increasing temperature. Similarly, the reduction ratios increased at temperatures below 1300 °C for different carbon sources; among them, the maximum reduction effect was obtained using graphite. When the temperature exceeded 1300 °C, the increasing trend of graphite decreased slightly. At 1350 °C, the maximum reduction effect was obtained using pulverized coal; meanwhile, the maximum reduction ratio of the sample was 51.77%.

### *Influence of different carbon sources on volatilization ratio of P*

The relationship between the volatilization ratio of P, temperature, and different reducing reagents is

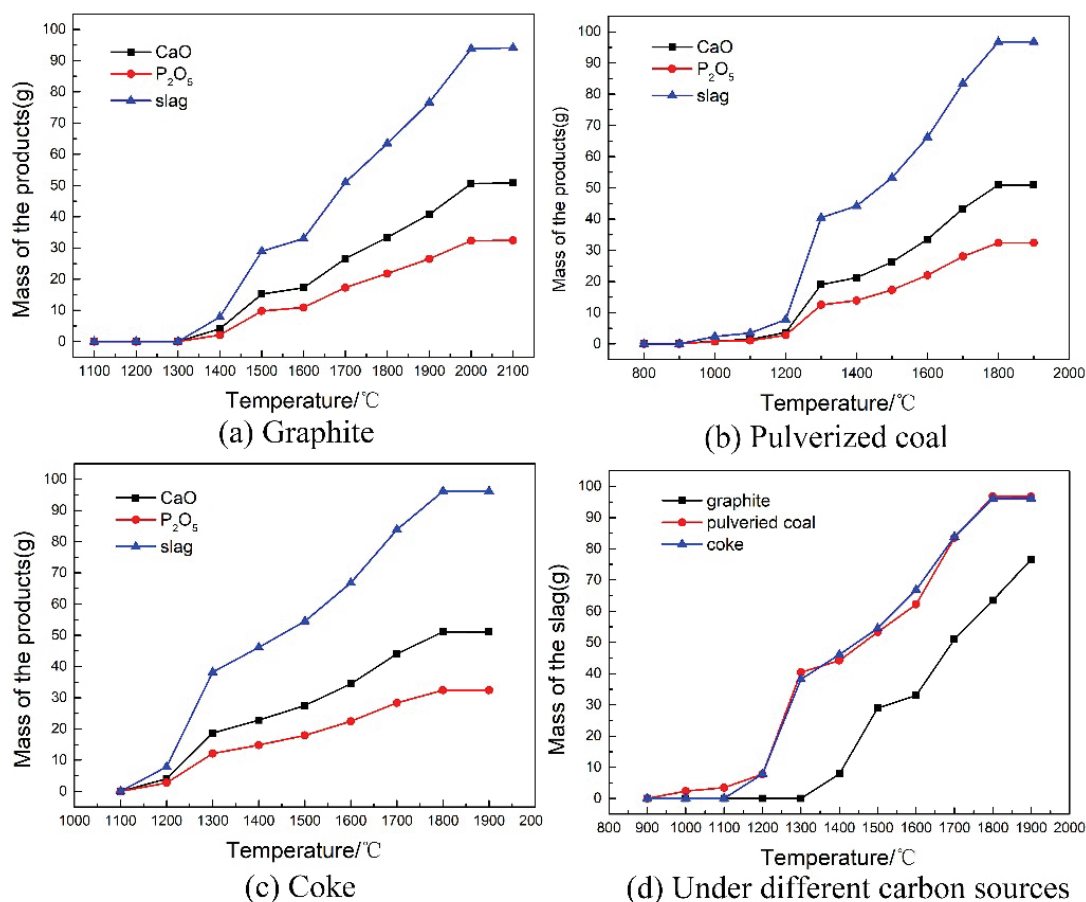


Figure 4. The relationship of temperature and mass of the products under different carbon sources.



shown in Figure 6. A similar trend was observed between the volatilization ratios of P and reduction ratios of the samples; moreover, the volatilization ratio of P increased with increasing temperature for different carbon sources. The volatilization effect of coke was the lowest, and those of graphite and pulverized coal were similar because the fixed carbon content in graphite was 99%, so it could fully contact with  $\text{Ca}_3(\text{PO}_4)_2$  which was produced by the self-decom-

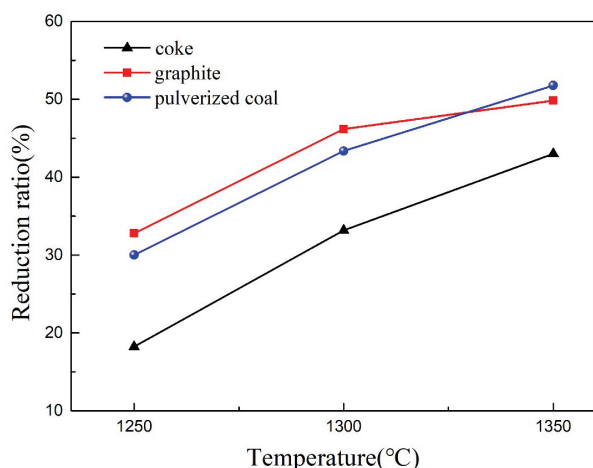


Figure 5. Effect of different carbon sources on the reduction ratio.

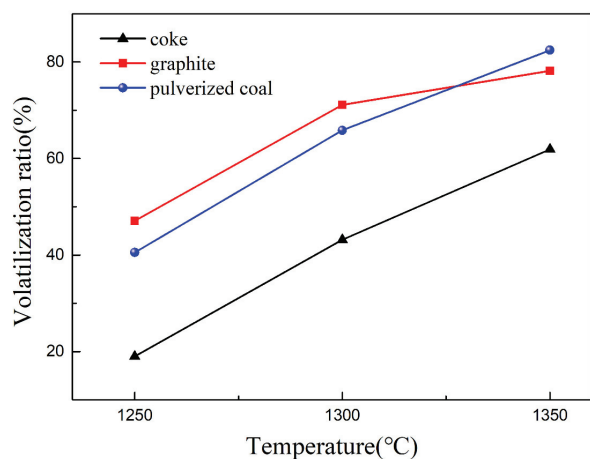


Figure 6. Effect of different carbon sources on the volatilization ratio of P.

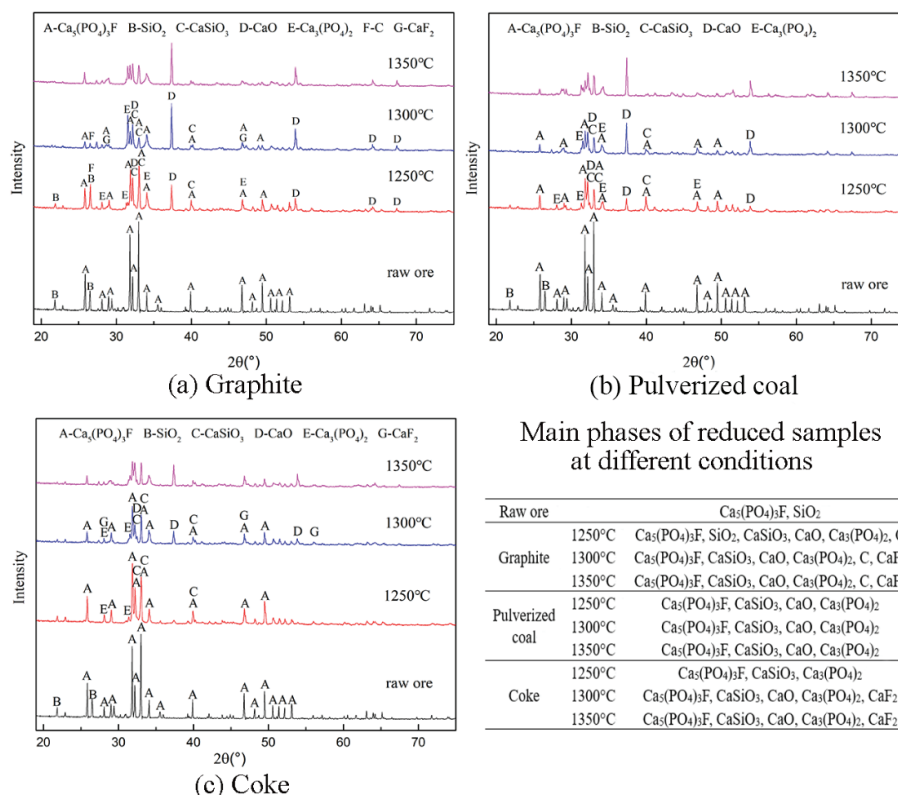
position of  $\text{Ca}_5(\text{PO}_4)_3\text{F}$ , increasing the contact area between reactants and thus promoting the reaction [24]. When pulverized coal, which had more crystal water and volatiles, was used as the reducing reagent and a small amount of  $\text{SiO}_2$  was contained in the phosphate rock and pulverized coal,  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  not only self-decomposed, but also combined with  $\text{SiO}_2$  to form  $\text{Ca}_3(\text{PO}_4)_2$  in the reduction process. The particle size of the pulverized coal was further reduced and

refined under the action of crystal water and volatiles. The reaction was promoted effectively by increasing the contact area between the carbon and reactants. The trend of change in the volatilization ratio of P under different carbon sources was the same at 1250–1300 °C; the increasing trend in the volatilization ratio of P using graphite as the reducing reagent decreased slightly above 1300 °C. When the temperature increased from 1250 to 1350 °C, the volatilization ratio of P reached a maximum of 82.44% when pulverized coal was used as the reducing reagent.  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and  $\text{MgO}$  in the volatiles were exposed and formed a low-temperature molten matrix with  $\text{CaO}$  as the degree of reaction increased [25], and the molten phase could accelerate the heat and mass transfers, which significantly promoted the reaction.

#### Phase analysis of reduced sample

The XRD phase analysis of the raw ore and reduced sample are shown for different carbon sources. Figure 7a shows the XRD pattern of the reduced sample when graphite is used as the reducing agent and the holding time is 60 min. At 1250 °C,  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  reacted with  $\text{SiO}_2$  and self-decomposed, and the peak intensity of  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  became weaker. Simultaneously, the diffraction peaks of  $\text{CaSiO}_3$ ,  $\text{CaO}$ ,  $\text{C}$  and  $\text{Ca}_3(\text{PO}_4)_2$  appeared. At 1300 °C, the peak intensity of  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  was weakened significantly, and the diffraction peak of  $\text{SiO}_2$  disappeared, indicating that the degree of reaction was increased.  $\text{SiO}_2$  in the raw ore completely reacted with  $\text{CaO}$ , but the yield of  $\text{CaO}$  was greater than consumption, which lead to the peak intensity of  $\text{CaO}$  being strengthened, and the diffraction peak of  $\text{CaF}_2$  appeared. When the temperature increased from 1300 to 1350 °C, no new diffraction peaks appeared in the XRD pattern and no substances disappeared. As the reaction proceeded,  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  self-decomposed and the diffraction peak became weaker.

Figure 7b shows the XRD pattern analysis of the reduced sample when the pulverized coal is used as the reduction reagent and the holding time is 60 min. At 1250 °C, the diffraction peak of  $\text{SiO}_2$  disappeared, and it completely reacted with  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  and  $\text{CaO}$  in the raw ore as the reaction proceeded, and the peak intensity of  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  was weakened. While the production of  $\text{CaO}$  was greater than that of consumption, the diffraction peaks of  $\text{CaSiO}_3$ ,  $\text{CaO}$  and  $\text{Ca}_3(\text{PO}_4)_2$  appeared. At 1300 °C, the peak intensities of  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  and  $\text{Ca}_3(\text{PO}_4)_2$  became weaker, but the peak intensity of  $\text{CaO}$  gradually increased. In the XRD pattern observed at 1350 °C, no new diffraction peaks appeared compared with those at 1300 °C, and



Main phases of reduced samples at different conditions

Raw ore	$\text{Ca}_5(\text{PO}_4)_3\text{F}$ , $\text{SiO}_2$
1250°C	$\text{Ca}_5(\text{PO}_4)_3\text{F}$ , $\text{SiO}_2$ , $\text{CaSiO}_3$ , $\text{CaO}$ , $\text{Ca}_3(\text{PO}_4)_2$ , $\text{C}$
Graphite	1300°C $\text{Ca}_5(\text{PO}_4)_3\text{F}$ , $\text{CaSiO}_3$ , $\text{CaO}$ , $\text{Ca}_3(\text{PO}_4)_2$ , $\text{C}$ , $\text{CaF}_2$
	1350°C $\text{Ca}_5(\text{PO}_4)_3\text{F}$ , $\text{CaSiO}_3$ , $\text{CaO}$ , $\text{Ca}_3(\text{PO}_4)_2$ , $\text{C}$ , $\text{CaF}_2$
Pulverized coal	1250°C $\text{Ca}_5(\text{PO}_4)_3\text{F}$ , $\text{CaSiO}_3$ , $\text{CaO}$ , $\text{Ca}_3(\text{PO}_4)_2$
	1300°C $\text{Ca}_5(\text{PO}_4)_3\text{F}$ , $\text{CaSiO}_3$ , $\text{CaO}$ , $\text{Ca}_3(\text{PO}_4)_2$
	1350°C $\text{Ca}_5(\text{PO}_4)_3\text{F}$ , $\text{CaSiO}_3$ , $\text{CaO}$ , $\text{Ca}_3(\text{PO}_4)_2$
Coke	1250°C $\text{Ca}_5(\text{PO}_4)_3\text{F}$ , $\text{CaSiO}_3$ , $\text{Ca}_3(\text{PO}_4)_2$
	1300°C $\text{Ca}_5(\text{PO}_4)_3\text{F}$ , $\text{CaSiO}_3$ , $\text{CaO}$ , $\text{Ca}_3(\text{PO}_4)_2$ , $\text{CaF}_2$
	1350°C $\text{Ca}_5(\text{PO}_4)_3\text{F}$ , $\text{CaSiO}_3$ , $\text{CaO}$ , $\text{Ca}_3(\text{PO}_4)_2$ , $\text{CaF}_2$

Figure 7. XRD analysis of the reduced samples at different conditions.

the peak positions were unchanged. The peak intensity of  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  gradually weakened and peak intensity of  $\text{CaO}$  increased due to self-decomposition as the reaction progressed.

Figure 7c shows the XRD pattern analysis of the reduced sample when coke is used as the reduction reagent and the holding time is 60 min. At 1250 °C,  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  reacted continuously and the peak intensity weakened gradually, diffraction peak of  $\text{SiO}_2$  disappeared, and  $\text{SiO}_2$  reacted with  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  and  $\text{CaO}$  completely. Simultaneously, the diffraction peaks of  $\text{CaSiO}_3$  and  $\text{Ca}_3(\text{PO}_4)_2$  appeared in the XRD pattern. At 1300 °C, the diffraction peak of  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  was weaker than that at 1250 °C.  $\text{CaSiO}_3$  reacted with  $\text{C}$  and the peak intensity weakened, but  $\text{CaO}$  was continuously generated, and the diffraction peaks of  $\text{CaO}$  and  $\text{CaF}_2$  appeared. At 1350 °C, no new diffraction peaks appeared, and the positions of the diffraction peaks remained unchanged. The peak intensity of  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  weakened and peak intensity of  $\text{CaO}$  was strengthened as the reaction proceeded.

### Microstructure analysis

The reduction samples with different carbon sources were analyzed at the microscopic level at 1350 °C respectively; the BSE and EDS of the samples are shown in Figure 8. At 1350 °C,  $\text{Ca}$ ,  $\text{O}$

and  $\text{P}$  were distributed uniformly in the whole region, forming particles of different sizes, and the particle size was mainly distributed in the 10–20  $\mu\text{m}$  range, and a small number of particles were between 50–100  $\mu\text{m}$ . Among them, the density of  $\text{Ca}$  and  $\text{O}$  was almost the same, but the density of  $\text{P}$  was different due to the different volatilization degree under different carbon sources. When pulverized coal was used as reducing agent, the volatility of  $\text{P}$  was the best at 1350 °C, and the density of  $\text{P}$  in slag was the lowest, which is consistent with the results of the XRD phase diagram. Under the conditions of 1350 °C and different reducing agents, the  $\text{CaO}$  content in slag was higher. Due to reduction and volatilization, only a small amount of  $\text{P}$  existed in  $\text{Ca}_3(\text{PO}_4)_2$ .

### CONCLUSION

1) The calculation results indicated that when the system pressure was 1 Pa, the mass of  $\text{P}$  in the gas phase first increased and then decreased with increasing temperature under different carbon sources, and a maximum mass of  $\text{P}$  was obtained at 1250 °C. When pulverized coal and coke were used as the reducing reagents, the melting initiation temperature and melting termination temperature could be red-

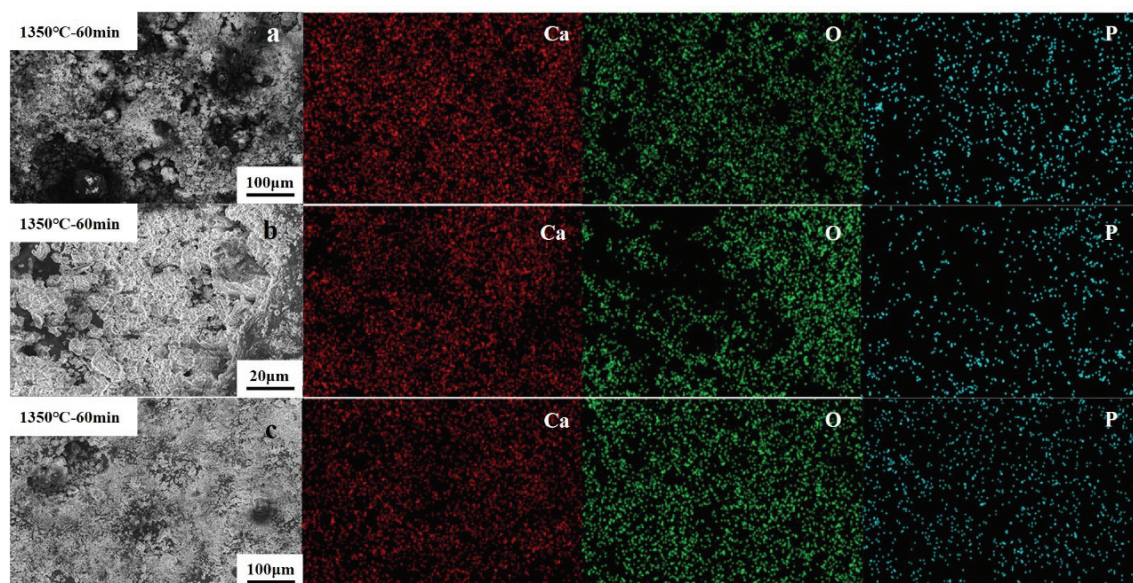


Figure 8. BSE and EDS of reduction samples (a - graphite, b - pulverized coal, c - coke).

uced effectively. The maximum reduction effect was obtained using graphite.

2) Experimental results showed that the reduction ratio of the sample and volatilization ratio of P increased with increasing temperature under different carbon sources. In comparison with coke, pulverized coal contained more crystal water and volatiles. During the reduction process, existence of the crystal water and volatiles promoted further decomposition and refinement of the pulverized coal particles, and the reduced particle size of pulverized coal increased the contact area between the carbon and reactants and promoted the reaction.

3) A comparison of the theoretical calculations with experimental results revealed that the optimum reduction agent in the vacuum carbothermic reduction experiment of low-grade phosphate rock was graphite. However, considering cost-effectiveness, pulverized coal had the highest benefit in actual production.

#### Acknowledgments

The authors are especially grateful for the financial support from the National Natural Science Fund of China (No. 51664003, 52064010) and Scholarship Contract for Overseas Talents (2019) No. 08.

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NAUČNI RAD

## UTICAJ RAZLIČITIH IZVORA UGLJENIKA NA VAKUUMSKU UGLJENOTERMIČKU REDUKCIJU FOSFATNE RUDE LOŠEG KVALITETA

*U ovoj studiji, uticaj različitih izvora ugljenika na karbotermičku redukciju niskokvalitetne fosfatne rude istražen je korišćenjem proračuna FactSage7.2 i eksperimenata redukcije pod vakuumom. Termodinamički proračuni su pokazali da je trend efekta za tri vrste redukcionih agenasa generalno konzistentan pod pritiskom od 1 Pa i dozom ugljenika od 14%. Efekat redukcije je bio maksimalan kada je grafit korišćen kao redukciono sredstvo, a maksimalna masa fosfora je dobijena na 1250 °C. Rezultati eksperimenta pod vakuumom su pokazali da se odnos redukcije i isparavanja fosfatne stene povećava sa temperaturom za različite izvore ugljenika. Maksimalni odnos redukcije dobijen je korišćenjem grafita u temperaturnom opsegu 1250-1300 °C. Redukcioni efekat praha uglja bio je optimalan na 1350 °C, kada su SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> i MgO bili izloženi formiranju eutektika niskog topljenja sa CaO zbog povećanog stepena reakcije i povećanih brzina prenosa toplote i mase. U ovom slučaju, postignut je maksimalni odnos redukcije uzorka od 51,77% i maksimalni odnos isparavanja fosfora od 82,44%. Uzimajući u obzir isplativost, ugalj u prahu je bio optimalan izvor ugljenika za tretman fosfatnih stena lošeg kvaliteta primenom vakuumske karbotermičke redukcije.*

*Ključne reči: vakuumska karbotermička redukcija; FactSage; izvori ugljenika; fosfatna ruda lošeg kvaliteta.*