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Distribution of P_2O_5 between P-rich Phase and Matrix Phase in P-bearing Steelmaking Slag

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Abstract: To recycle the phosphorus in P-bearing steel-making slag and use the slag as phosphate fertilizer, it is necessary to study the distribution of P_2O_5 between the P-rich phase and matrix phase in P-bearing steel-making slag. The addition of MgO and MnO into the slag has no effect on the phosphorus form of existence in the slag and has little effect on the $\%(P_2O_5)_{SS}$. In contrast, Na_2O and CaF_2 in the slag change the phosphorus form of existence in the slag and increase $\%(P_2O_5)_{SS}$ obviously. L_p' , $\gamma_{P_2O_5(SS)}$, $\gamma_{P_2O_5(M)}$, $C_{P(M)}$ and $C_{P(SS)}$ were calculated, and it was found that $\%(CaO)$, $\%(T.Fe)$ and $\%(P_2O_5)$ in the P-rich phase and matrix phase significantly affect L_p' . MnO and MgO in the slag have little effect on the distribution of P_2O_5 between the P-rich phase and matrix phase, whereas Na_2O and CaF_2 affect the distribution of P_2O_5 between the P-rich phase and matrix phase.

Keywords: slag phosphate fertilizer, phosphorus, resources recovery, P_2O_5 distribution, P-bearing steelmaking slag

Introduction

With the rapid development of steel industry in China, the cumulative amount of slag has increased to more than 200 million tons, which affects the environment. Owing to the dephosphorization in steel-making process and the past use of phosphorus-rich ore in recent years, slags rich in phosphorus are being produced. If P_2O_5 in

the slag can be enriched and separated, the separated P_2O_5 phase may be used as phosphoric fertilizer or phosphoric fertilizer additives, while the rest of the ingredients may be recycled in the iron- and steel-making processes, e.g., sintering, hot metal desiliconization, and hot metal dephosphorization process. If steel slag recycling is realized, the utilization of converter slag in agriculture will minimize environmental pollution and create financial benefit.

The fertilizer efficiency of slag phosphate fertilizer depends on $\%(P_2O_5)$ and P_2O_5 solubility. The $\%(P_2O_5)$ in slag phosphate fertilizer is related to the phosphorus enrichment and separation from the slag, while the degree of phosphorus enrichment is dependent on the phosphorus distribution among the different phases in the slag [1–3]. Therefore, to efficiently recover phosphorus resources from slag to use as fertilizer, it is critical to study the phosphorus distribution between the P-rich phase and matrix phase in slag. To date, phosphorus existence form in slag and phosphorus distribution between steel and slag have been extensively studied [3, 4, 5, 6, 7]. Inoue and Suito [8] found that the phosphorous transfer rate from slag to 20 to 50 μm long dicalcium silicate ($2CaO \cdot SiO_2$) particles is considerably fast and the $2CaO \cdot SiO_2$ particle changes to the particle with the composition of $nCaO \cdot SiO_2 \cdot 3CaO \cdot P_2O_5$ (for short $nC_2S \cdot C_3P$) solid solution within 5 s. Shimauchi et al. [9] studied the distribution of P_2O_5 between solid dicalcium silicate and liquid phases in the $CaO-SiO_2-Fe_2O_3$ system, and found that high P_2O_5 content and reasonable T.Fe content were controlled to show the high distribution ratio, and the addition of MgO and MnO has no effect on the distribution ratio of P_2O_5 . Panlevani et al. [10] studied the distribution of P_2O_5 between the $nC_2S \cdot C_3P$ solid solution and liquid phase, and investigated the effect of MgO, MnO, and Al_2O_3 on the distribution of P_2O_5 in slags with variable iron oxide (FeO or Fe_2O_3) content.

There is, however, lack of studies regarding the effect of CaF_2 and Na_2O on the distribution of P_2O_5 between P-rich phase and matrix phase in the slag. In this paper, the effect of MnO, MgO, Na_2O and CaF_2 on the phosphorus existence form and the distribution ratio of P_2O_5 between P-rich phase and matrix phase in slag was

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studied systematically, $\gamma_{\text{P}_2\text{O}_5}$ and C_P in P-rich slag phase and matrix phase were analyzed, additionally, the effect of adding different oxides on distribution ratio of P₂O₅ between P-rich slag phase and matrix phase in slag was discussed, which provide the theoretical foundation for phosphorus enrichment and separation in slag, and provide the necessary research basis for the resource utilization of P-bearing steelmaking slag using as slag phosphate fertilizer.

Research method

Reagent grades CaO, SiO₂, Fe₂O₃, P₂O₅, MgO, MnCO₃, CaF₂ and Na₂CO₃ were mixed in various ratios to produce the CaO-SiO₂-Fe₂O₃-P₂O₅ slag system. To investigating the effect of other elements on the distribution of P₂O₅ between the P-rich phase and matrix phase, Na₂O, CaF₂, MgO and MnO were also added. The mixing conditions are summarized in Table 1. Figure 1 shows the compositional range of slags in the CaO-SiO₂-Fe₂O₃ ternary phase diagram calculated by using the FactSage 6.3 for samples X. As shown in Figure 1, all experimental slags were in the dicalcium silicate (C₂S) primary zone, C₂S precipitated first during the cooling process, and then nC₂S-C₃P solid solution (mainly Ca₁₅(PO₄)₂(SiO₄)₆ and Ca₅(PO₄)₂SiO₄) formed. Most of the iron oxide would be in the form of FeO in steelmaking condition, but Fe₂O₃ was used as iron oxide in this experiment and the heating was carried out under the air atmosphere, the reasons are as follow: (1) Ito et al. [8] disclosed that the distribution behavior of P₂O₅ between solid solution and liquid phases was not different, when the iron oxide changed from FeO to Fe₂O₃. (2) Shimauchi et al. [9] found that FeO was solved into the solid solution but the content of Fe₂O₃ in solid solution was negligible small. (3) According

Figure 1: Observed slag composition in the ternary phase diagram of the CaO-SiO₂-Fe₂O₃ system.

to the preliminary experiments, it was found that phosphorus enrichment behavior between solid solution and liquid phases was not affected, when the iron oxide changed from FeO to Fe₂O₃.

The mixed slags (200 g) were placed in magnesia crucible, 60 mm in diameter and 100 mm long that were subsequently placed inside graphite crucibles and heated in a MoSi₂ electric resistance furnace up to 1773 K. The temperature was maintained for 30 min to ensure the slag fully melting. Then, the slags were cooled to 1623 K at 3 K/min and maintained at this temperature for 1 h to fully promote the precipitation of 3CaO·P₂O₅. Then, they were cooled to 1423 K at 3 K/min, and the furnace was subsequently turned off and the slag samples were left to cool in the furnace (Figure 2). The phase morphology of the prepared slag samples was observed by an S-360 scan electron microscope,

Table 1: Composition of the synthetic slag samples (mass fraction, %).

No.	CaO	SiO ₂	Fe ₂ O ₃	P ₂ O ₅	MgO	MnO	CaF ₂	Na ₂ O
A	42.86	17.14	30	10				
A(5%MgO)	39.29	15.71	30	10	5			
A(10%MgO)	35.71	14.29	30	10	10			
A(5%MnO)	39.29	15.71	30	10		5		
A(10%MnO)	35.71	14.29	30	10		10		
A(3%Na ₂ O)	40.71	16.29	30	10				3
A(6%Na ₂ O)	38.57	15.43	30	10				6
A(3%CaF ₂)	40.71	16.29	30	10			3	
A(6%CaF ₂)	38.57	15.43	30	10			6

Figure 2: Experimental conditions for precipitation of C_2S - C_3P solid solution.

and each phase composition was analyzed by a Tracor Northern spectrometer. After each experiment, the slags were ground to less than 300 mesh (48 μm), and mineralogical phases were determined by XRD analysis. Diffraction patterns were measured in a 2θ range of 10° - 90° using copper K_α radiation of 40 kV and 30 mA, and the scan speed was $5^\circ/min$.

Experiment results

Figure 3 shows a SEM-BSE image (Scanning Electron Microscope- Back scattered Electron Imaging) of a sample after cooling. The EDS data for the sample is given in Table 2. Figure 4 shows the X-ray diffraction results of synthetic slag samples.

The results suggest that the P-bearing slag mainly consists of P-rich phase, matrix phase, and RO phase. The $\%(P_2O_5)$ in matrix phase is low, the matrix phase mainly comprise of $nCaO \cdot SiO_2$ and merwinite ($Ca_3MgSi_2O_8$), and the RO phase mainly consists of iron oxide or iron and magnesium oxide.

$\%(P_2O_5)$ in the P-rich phase in A slag is about 20%, the phosphorus in P-rich phase is mainly in the existence of $6C_2S \cdot C_3P$ solid solution. For adding MgO or MnO into the $CaO \cdot SiO_2 \cdot P_2O_5 \cdot Fe_2O_3$ slag, MnO and MgO mainly enters into RO phase to form $MnFe_2O_4$ and $MgFe_2O_4$, and has little change in the $\%(P_2O_5)$ in P-rich phase (also about 20%), so which has little effect on the degree of phosphorus enrichment and phosphorus occurrence form.

In the A(3% Na_2O) slag, the added Na_2O mainly replaces calcium ions(Ca^{2+}) in the P-rich phase ($6C_2S \cdot C_3P$ solid solution) to form $C_2S \cdot C_3P$ and $Na_2Ca_4(PO_4)_2SiO_4$, finally the P-rich phase is mainly $6C_2S \cdot C_3P$, $C_2S \cdot C_3P$ exists along with $Na_2Ca_4(PO_4)_2SiO_4$, and generally contains about 23–26%

Figure 3: SEM-BSE image of experimental samples (1- P-rich phase, 2- RO phase, 3- Matrix phase).

Table 2: Chemical compositions of each phase from sample in Figure 3 by EDS (mass fraction, %).

No.	Main phase	Na ₂ O	CaF ₂	MnO	MgO	SiO ₂	P ₂ O ₅	CaO	Fe ₂ O ₃
A	P-rich phase	0	0	0	2.95	15.24	20.75	58.90	2.16
	RO phase	0	0	0	5.30	0.07	0.17	0.61	93.85
	Matrix phase	0	0	0	11.46	31.29	3.56	53.68	0
A(5%MgO)	P-rich phase	0	0	0	0.58	12.98	20.76	65.24	0.44
	RO phase	0	0	0	5.92	0.40	0	1.02	92.66
	Matrix phase	0	0	0	7.83	21.98	6.23	61.37	2.58
A(10%MgO)	P-rich phase	0	0	0	2.63	15.30	19.66	60.82	1.60
	RO phase	0	0	0	27.53	0	0	0.60	71.87
	Matrix phase	0	0	0	7.74	23.52	9.33	57.76	1.66
A(5%MnO)	P-rich phase	0	0	1.22	0.34	12.83	22.62	62.36	0.64
	RO phase	0	0	6.68	1.38	0.15	0	0.97	90.82
	Matrix phase	0	0	2.02	7.05	26.84	2.59	57.81	3.70
A(10%MnO)	P-rich phase	0	0	0	0	14.64	19.43	64.96	0.97
	RO phase	0	0	11.41	4.43	0	0	0.73	83.43
	Matrix phase	0	0	2.31	9.59	29.90	1.79	54.57	1.84
A(3%Na ₂ O)	P-rich phase	2.16	0	0	0	14.58	23.63	59.61	0
	RO phase	0	0	0	7.82	0	0	0	92.18
	Matrix phase	1.47	0	0	9.54	23.13	2.23	63.60	1.03
A(6%Na ₂ O)	P-rich phase	12.31	0	0	0	8.63	31.74	47.01	0.31
	RO phase	0.85	0	0	8.03	0.35	0.15	0	90.62
	Matrix phase	3.70	0	0	10.52	22.51	1.45	60.30	1.25
A(3%CaF ₂)	P-rich phase	0	4.43	0	0	3.30	34.00	58.11	0.15
	RO phase	0	0.53	0	5.42	0.14	0	0.99	92.93
	Matrix phase	0	0	0	9.29	27.98	1.60	58.40	2.73
A(6%CaF ₂)	P-rich phase	0	4.59	0	0	2.71	37.75	54.85	0.09
	RO phase	0	0.30	0	6.12	0	0	2.84	90.74
	Matrix phase	0	0	0	10.11	31.95	1.82	53.03	3.08

P₂O₅, and its particle size increased to more than 100 μm. In the A(6%Na₂O) slag, %(P₂O₅) in the P-rich phase further increased to 32%, and owing to the binding capacity of sodium ions(Na⁺) combine with phosphate ions((PO₄)³⁻) are stronger than calcium ions(Ca²⁺), calcium ions(Ca²⁺) in phosphorus-rich phase (6C₂S-C₃P or Na₂Ca₄(PO₄)₂SiO₄) are replaced by sodium ions(Na⁺), then Na₃PO₄ are formed, so the phosphorus existence form is changed.

In the A(3%Ca₂F) slag, %(P₂O₅) in the P-rich phase is also obviously higher than in the A slag. The added fluorine mainly enters the P-rich phase to form fluorapatite (Ca₅(PO₄)₃F), and %(P₂O₅) in the P-rich phase is generally about 34%, the particle size further increased to more than 100 μm. In the A(6%Ca₂F) slag, %(P₂O₅) in the P-rich phase is increased to 37%, whereas the particle size remained the same as that in the A(3%Ca₂F) slag, and the content and crystallization rate fluorapatite (Ca₅(PO₄)₃F) in the P-rich phase increased with increasing of CaF₂ content. The addition of CaF₂ significantly increases the %(P₂O₅) in the P-rich phase. Fluorapatite cannot be dissolved in 2% citric acid solution, therefore,

the P₂O₅ solubility of slag decreases [11, 12]. To further verify existence form of phosphorus and fluorine in P-bearing slag, the phase diagram at 1273 K was calculated in CaO-P₂O₅-CaF₂ system using the FactSage 6.3 software. As shown in Figure 5, P and Q in the diagram correspond to the area of A(3%Ca₂F) slag and A(6%Ca₂F) slag respectively. It shows that the phosphorus and fluorine mainly precipitated as fluorapatite crystal during the slag cooling process, which is consistent with the results of XRD.

Discussion

Based on SEM and EDS data in Figure 3 and Table 2, the P-bearing slag consists of P-rich phase, matrix phase, and RO phase, and the phosphorus is mainly in the P-rich phase and matrix phase. To improve dephosphorization and to increase the applications of P-bearing slag, the distribution of P₂O₅ between the P-rich phase and matrix phase is discussed in this paper.

Figure 4: XRD results of different slag composition modification.

Figure 5: The CaO- P_2O_5 - CaF_2 ternary phase diagram at 1273 K that calculated by FactSage 6.3.

The effect of slag composition on L_p' between P-rich phase and matrix phase

The phosphorus in slag is transferred from the matrix phases to the $2CaO \cdot SiO_2$ particles to form $nC_2S \cdot C_3P$ solid solution. The distribution ratio of P_2O_5 between P-rich

phase and matrix phase ($L_p' = \%(P_2O_5)_{SS} / \%(P_2O_5)_M$) is used to represent the degree of phosphorus enrichment in the slag in this study, $\%(P_2O_5)_{SS}$ stands for the P_2O_5 mass fraction in the P-rich phase, and $\%(P_2O_5)_M$ stands for the P_2O_5 mass fraction in the matrix phase. The bigger the L_p' is, the more phosphorus is transferred from the matrix to the P-rich phase.

The relation between L_p' and $\%(T.Fe)$ in the matrix phase of different slag systems is shown in Figure 6. L_p' increases with increasing of $\%(T.Fe)$ in the matrix phase. The addition of MgO and MnO into the $CaO \cdot SiO_2 \cdot Fe_2O_3 \cdot P_2O_5$ slag system affects the L_p' negligibly. $\%(P_2O_5)_{SS}$ increases with increasing Na₂O in the slag, however, since $\%(P_2O_5)_M$ also increases, L_p' does not change. However, L_p' increases evidently with increasing CaF_2 in the slag. It is mainly due to that the melting point of slag is reduced effectively, the fluidity of the slag is increased, the phosphorus transfer from matrix phase to P-rich phase in the slag is promoted, and a new phase fluorapatite is formed with the addition CaF_2 into the slag, so the $\%(P_2O_5)_{SS}$ increases significantly.

Figure 6: The effect of $\%(T.Fe)$ in the matrix phase on L_p' in different slag systems.

The basicity of matrix phase has an important effect on L_p' , the $\%(CaO)$ of the matrix phase is used to show the basicity, as shown in Figure 7. In the $CaO \cdot SiO_2 \cdot Fe_2O_3 \cdot P_2O_5 \cdot X$ ($X = MgO, MnO, Na_2O$ and CaF_2) slag system, L_p' decreases with increasing of $\%(CaO)$ in the matrix phase.

The effect of slag composition on the activity coefficient of P_2O_5

As the P-rich phase and the matrix phase of the final slag is in equilibrium, the activities of P_2O_5 in both

Figure 7: The effect of % (CaO) in the matrix phase on L_p' in different slag systems.

phases are the same, thus, L_p' is proportional to the ratio of the activity coefficient of P₂O₅ between the matrix phase and P-rich phase, as shown in eq. (1), where a is the activity; γ is the activity coefficient, X is the mol fraction, and k is the coefficient for converting the mass percentage to mol fraction. Subscripts P₂O₅ (M) and P₂O₅ (SS) denote the activity and activity coefficient of P₂O₅ in the matrix phase and P-rich phase, respectively. The activity coefficient of P₂O₅ in the matrix phase is calculated by using a regular solution model [7], while the activity coefficient of P₂O₅ in the P-rich phase is calculated by using eq. (1).

$$L_p = \frac{(\%P_2O_5)_{SS}}{(\%P_2O_5)_M} = k \frac{a_{P_2O_5(SS)} \times \gamma_{P_2O_5(M)}}{a_{P_2O_5(M)} \times \gamma_{P_2O_5(SS)}} = k \frac{\gamma_{P_2O_5(M)}}{\gamma_{P_2O_5(SS)}} \quad (1)$$

Activity coefficient of P₂O₅ in the P-rich phase

Figures 8 and 9 show the relation between % (T.Fe), % (CaO) in matrix phase and the $\gamma_{P_2O_5(SS)}$ in different slag systems. The $\gamma_{P_2O_5(SS)}$ decreases with the addition of MgO, MnO, Na₂O, and CaF₂ in the slag, whereas the $\gamma_{P_2O_5(SS)}$ decreases minimally for the addition MgO, MnO, and CaF₂ in the slag, and the $\gamma_{P_2O_5(SS)}$ decreases significantly after adding Na₂O. Meanwhile, $\gamma_{P_2O_5(SS)}$ increases with decreasing the % (CaO) in the matrix phase in different slag systems. In the regular model, the interaction energy between other cations and Ca²⁺ is negative, and the $\gamma_{P_2O_5(SS)}$ and Ca²⁺ content in the slag is a negative correlation, which results in $\gamma_{P_2O_5(SS)}$ increases with decreasing Ca²⁺ when the % (CaO) in the slag decreases.

Figure 8: The effect of % (T.Fe) in the matrix phase on the $\gamma_{P_2O_5(SS)}$ in different slag systems.

Figure 9: The effect of slag compositions on the $\gamma_{P_2O_5(SS)}$ at different % (CaO) in the matrix phase.

Figure 10 shows the relation between $\gamma_{P_2O_5(SS)}$ and the $\gamma_{P_2O_5(M)}$ in different slag systems. $\gamma_{P_2O_5(SS)}$ minimally changes with increasing % (MgO) and % (MnO) in the slag, whereas $\gamma_{P_2O_5(SS)}$ increases with increasing % (Na₂O) and % (CaF₂) in the slag. In the CaO-SiO₂-Fe₂O₃-P₂O₅-X (X = MgO, MnO, Na₂O and CaF₂) slag system, $\gamma_{P_2O_5(SS)}$ increases with increasing % (MnO), % (MgO) and % (CaF₂), whereas $\gamma_{P_2O_5(SS)}$ decreases with increasing % (Na₂O).

Activity coefficient of P₂O₅ in the matrix phase

Figures 11 and 12 show respectively the relation between % (T.Fe), % (CaO) in the matrix phase and the $\gamma_{P_2O_5(M)}$ in

Figure 10: The effect of $\%(P_2O_5)_{SS}$ on the $\gamma_{P_2O_5(SS)}$ in different slag systems.

Figure 11: The effect of $\%(CaO)$ in the matrix phase on the $\gamma_{P_2O_5(M)}$ in different slag systems.

Figure 12: The effect of $\%(T.Fe)$ in the matrix phase on the $\gamma_{P_2O_5(M)}$ in different slag systems.

different slag systems. The $\gamma_{P_2O_5(M)}$ minimally changes with increasing $\%(MgO)$, $\%(MnO)$ and $\%(CaF_2)$ in the slag, whereas $\gamma_{P_2O_5(M)}$ decreases with increasing $\%(Na_2O)$ in the slag. Meanwhile, $\gamma_{P_2O_5(M)}$ increases with decreasing $\%(CaO)$ in the matrix phase. As the P-rich phase and the matrix phase of the final slag are in equilibrium, the activities of P_2O_5 in both phases are the same (see eq. (1)), when the $\%(P_2O_5)_{SS}$ and the matrix phase are constant, $\gamma_{P_2O_5(SS)}$ also increases with decreasing $\%(CaO)$, which is consistent with the results shown in Figure 9.

The effect of slag composition on the phosphorus capacity

Phosphorus capacity (C_P) is used to judge the capacity of a slag to contain phosphorus. The P-rich phase and the matrix phase in the slag are regarded as two different slag systems and the C_P in the P-rich phase ($C_{P(SS)}$) and the matrix phase ($C_{P(M)}$) are studied to analyze the phosphorus distribution between P-rich phase and matrix phases. The C_P was calculated by using eq. (2) [13].

$$\log C_P = 0.51 \times (23N_{CaO} + 17N_{MgO} + 8N_{Fe_2O_3} + 33N_{Na_2O} + 20N_{CaF_2} + 13N_{MnO} - 26N_{P_2O_5}) + \frac{29920}{T} - 19.280 + \log(\%P)/N_{P_2O_5}^{1/2} \quad (2)$$

Phosphorus capacity of the P-rich phase

Figures 13 and 14 show respectively the relation between $\%(T.Fe)$, $\%(CaO)$ in matrix phase and $C_{P(SS)}$ for in slag systems. $C_{P(SS)}$ increases with increasing MgO , MnO , Na_2O and CaF_2 in the slag. $C_{P(SS)}$ increases with increasing $\%(CaO)$ in the matrix phase, as shown in Figure 13. Figure 14 shows that when the $\%(T.Fe)$ in matrix phase is less than 2%, $C_{P(SS)}$ decreases with increasing $\%(T.Fe)$ in the matrix phase, whereas when $\%(T.Fe)$ in the matrix phase is more than 2%, $C_{P(SS)}$ increases with increasing $\%(T.Fe)$ in the matrix phase.

It can be seen from Figure 15 that $C_{P(SS)}$ linearly decreases with increasing $\%(P_2O_5)_{SS}$. $C_{P(SS)}$ is lowest in the slag with CaF_2 , whereas $C_{P(SS)}$ is highest in the slag with Na_2O , which is consistent with the results of Suito [14]. The decreasing C_P means that the capacity of containing phosphorus decreases as well.

Phosphorus capacity of the matrix phase

Figures 16 and 17 show respectively the relation between $\%(T.Fe)$, $\%(CaO)$ in matrix phase and $C_{P(M)}$ in different slag systems. $C_{P(M)}$ increases with the addition of MgO ,

Figure 13: The effect of $\%(\text{CaO})$ in the matrix phase on $C_{P(SS)}$ in different slag systems.

Figure 14: The effect of $\%(\text{TFe})$ in the matrix phase on $C_{P(SS)}$ in different slag systems.

MnO, Na_2O and CaF_2 into the slag, and $C_{P(M)}$ increases with increasing $\%(\text{CaO})$ in the matrix phase. From Figure 18, it can be seen that when $\%(\text{P}_2\text{O}_5)_M$ is less than 3%, $C_{P(M)}$ linearly increases with increasing $\%(\text{P}_2\text{O}_5)_M$. When $\%(\text{P}_2\text{O}_5)_M$ is more than 3%, $C_{P(M)}$ minimally changes with increasing $\%(\text{P}_2\text{O}_5)_M$. $C_{P(M)}$ is highest for the slag with Na_2O , and lowest in the slag with CaF_2 .

Conclusions

The effect of slag composition on phosphorus existence form in P-bearing slag was well researched, and the

Figure 15: The effect of $\%(\text{P}_2\text{O}_5)_{SS}$ on $C_{P(SS)}$ in different slag systems.

Figure 16: The effect of $\%(\text{CaO})$ in the matrix phase on $C_{P(M)}$ in different slag systems.

Figure 17: The effect of $\%(\text{TFe})$ in the matrix phase on $C_{P(M)}$ in different slag systems.

Figure 18: The effect of $\%(P_2O_5)_M$ on $C_{P(M)}$ in different slag systems.

distribution behavior of P_2O_5 between P-rich phase and matrix phase was analyzed. The key findings are as follows:

- (1) The slag is composed of P-rich phase, matrix phase, and RO phase. Phosphorus in the slag is mainly in the form of nC_2S-C_3P solid solution in the P-rich phase. For $CaO-SiO_2-Fe_2O_3-P_2O_5-X$ ($X = MgO, MnO, Na_2O$, and CaF_2 respectively) slag system, MgO and MnO are in RO phase and have no effect on the phosphorus existence form in the slag and the $\%(P_2O_5)_{SS}$. Na_2O and CaF_2 in the slag change the phosphorus existence form in the slag, and significantly increase the $\%(P_2O_5)_{SS}$.
- (2) With increasing $\%(T.Fe)$ and decreasing $\%(CaO)$ in the matrix phase, L_p' increases. MnO and MgO have little effect on L_p' , whereas Na_2O and CaF_2 strongly affect L_p' . Furthermore, L_p' clearly increases with increasing CaF_2 in the slag.
- (3) $\%(CaO)$ in the slag strongly affect $\gamma_{P_2O_5(SS)}$ and $\gamma_{P_2O_5(M)}$. Both $\gamma_{P_2O_5(SS)}$ and $\gamma_{P_2O_5(M)}$ decrease with increasing $\%(CaO)$ and $\gamma_{P_2O_5(SS)}$ increases with increasing $\%(P_2O_5)$ in the slag. MgO , MnO and CaF_2 in the slag minimally affects $\gamma_{P_2O_5(SS)}$ and $\gamma_{P_2O_5(M)}$, whereas Na_2O in the slag causes $\gamma_{P_2O_5(SS)}$ and $\gamma_{P_2O_5(M)}$ to decrease obviously.
- (4) With increasing $\%(P_2O_5)_{SS}$, $C_{P(SS)}$ decreases and $C_{P(M)}$ increases. When $\%(T.Fe)$ in the matrix phase is less than 2%, $C_{P(SS)}$ decreases with increasing $\%(T.Fe)$ in

the matrix phase. When $\%(T.Fe)$ in the matrix phase is more than 2%, $C_{P(SS)}$ increases with increasing $\%(T.Fe)$ in the matrix phase. For $\%(P_2O_5)_M$ is less than 3%, C_P linearly increases with increasing $\%(P_2O_5)_M$. For $\%(P_2O_5)_M$ is more than 3%, $C_{P(M)}$ minimally changes with the increasing $\%(P_2O_5)_M$. $C_{P(SS)}$ and $C_{P(M)}$ increase with increasing $\%(CaO)$ in the matrix phase. In the $CaO-SiO_2-Fe_2O_3-P_2O_5-X$ ($X = MgO, MnO, Na_2O$ and CaF_2) slag system, $C_{P(SS)}$ and $C_{P(M)}$ are highest when Na_2O is added and lowest when CaF_2 is added.

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