Electric smelting of phosphorites with production of a ferroalloy, calcium carbide and sublimation of phosphorus

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Abstract. The article presents the results of a study of the interaction of phosphorites from the Chulaktau deposit of the Karatau basin with coke and steel shavings. The studies were carried out by computer thermodynamic modeling using the HSC-10 software package, together with mathematical planning of experiments, as well as by electric phosphorite melting in an electric arc furnace. On the basis of the conducted studies it was established that the joint formation of intermediate products from the systems $Ca_3(PO_4)_2$-SiO_2-C-Fe is possible at the temperature > 1635-1702ºC. Based on the obtained volumetric and planar images of the coke and steel shavings effect on the technological parameters of the phosphorite's electric smelting, it was found that in order to produce FS25 grade ferrosilicon containing 20-30% of Si and calcium carbide with a capacity of 245.1-248.1 dm^3/kg (2nd grade), the process should be carried out in the presence of 52-58% of coke and 24.4-38% of steel shavings. In this case, the extraction degree of silicon into the ferroalloy was 70-80%, and calcium into calcium carbide – 60-70%.

Keywords: phosphorite, thermodynamic modeling, electrical melting, calcium carbide, ferroalloy.

1. Introduction

Producing fertilizers from phosphate raw materials is possible not only on the basis of wet and dry phosphoric acid, but also directly from phosphorites [1-6]. The bulk of fertilizers, however, is produced using phosphoric acid.

The average P_2O_5 content in Karatau phosphorites is 24.5%. To obtain wet phosphoric acid, phosphorite must contain ≥28% of P_2O_5 [1]. Therefore, the phosphorites are concentrated using usually flotation or chemical methods. So, flotation of nodular phosphorites containing 9-18% of P_2O_5 makes it possible to produce a 25-35% P_2O_5 concentrate [7], and flotation of shell phosphorites containing 4-7% of P_2O_5 – a 28.5-35% P_2O_5 concentrate [8-10]. A phosphate concentrates with 26-27.9% of P_2O_5 was obtained from phosphorite containing 16.2% of P_2O_5 by nitric acid concentration [11], and when using acetic and formic acids, it is possible to obtain a 30-35% P_2O_5 phosphate concentrate [12]. The chemical concentration of phosphorites based on the extraction of calcium into solution was shown in [13]. Production of phosphoric acid from phosphate concentrates is carried out using sulfuric, nitric, hydrochloric, fluorosilic-ic, and hydrofluoric acids [14-17]. Despite the fact that the nitric acid extraction makes it possible to obtain 27-35% P_2O_5 phosphoric acid, hydrochloric acid extraction – 55-58% P_2O_5 phosphoric acid, and fluorosilicic acid one – 25-30% P_2O_5 phosphoric acid, the main method for producing wet phosphoric acid is decomposition of phosphate concentrates with a mixture of aqueous solutions of sulfuric and phosphoric acids according to the equation:

$$Ca_3(PO_4)_3F + 2H_2SO_4 + H_3PO_4 + mH_2O = (n+3)H_3PO_4 + 5CaSO_4 \cdot mH_2O + HF \quad (1)$$
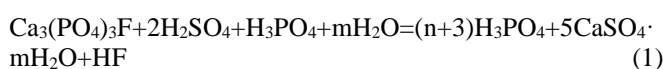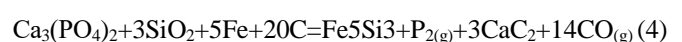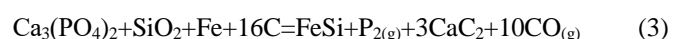
Disadvantages of this method are the high sulfuric acid consumption and formation of a large amount of waste – phosphogypsum (4.27-6.58 tonnes per 1 tonne of P_2O_5 in terms of dry dihydrate) [18]. Less stringent requirements for P_2O_5 content (≥21%) are imposed on phosphorites used for producing yellow phosphorus by the electrothermal method [1]. However, electric smelting of these phosphorites is accompanied by the formation of waste slag (10-12 tonnes per 1 tonne of phosphorus), which not only occupies land, but also has a limited demand in the construction industry because it contains 2-2.5% of P_2O_5, which, in the presence of moisture, emits a poisonous gas – phosphine.

2. Materials and methods

The main components of Karatau and Aktobe phosphorites are P_2O_5 (16-27%), and, in addition, CaO (20-44%) and SiO_2 (14-55%). Therefore, the phosphorites are a potential source for obtaining products containing calcium and silicon. In this regard, we have developed a technology for the processing of phosphorites by electric smelting with the simultaneous production of siliceous ferroalloy, calcium carbide and stripping of phosphorus into the gas phase.

The proposed method for processing phosphorites is based on the following reactions:

$$Ca_3(PO_4)_2 + 2SiO_2 + Fe + 16C = FeSi_2 + P_{2(g)} + 3CaC_2 + 12CO_{(g)} \quad (2)$$

$$Ca_3(PO_4)_2 + SiO_2 + Fe + 16C = FeSi + P_{2(g)} + 3CaC_2 + 10CO_{(g)} \quad (3)$$

$$Ca_3(PO_4)_2 + 3SiO_2 + 5Fe + 20C = Fe_5Si_3 + P_{2(g)} + 3CaC_2 + 14CO_{(g)} \quad (4)$$

$$Ca_3(PO_4)_2 + SiO_2 + 3Fe + 16C = Fe_3Si + P_{2(g)} + 3CaC_2 + 10CO_{(g)} \quad (5)$$

From a thermodynamic point of view, these reactions become possible at temperatures of above 1702.8; 1692.4; 1635.1 and 1639.2, respectively (Table 1, shaded area).

We have previously shown [20] that at the interaction of $Ca_3(PO_4)_2$ with silicon dioxide, carbon, and iron under equilibrium conditions, at a temperature of 1850-1950°C, it is possible to obtain calcium carbide with a capacity of 300-

360 dm^3/kg and FS45 ferrosilicon (39-42% of Si) and to achieve the complete sublimation of phosphorus into gas.

This article examines the results of electric smelting of Chulaktau phosphorites (Karatau basin) with production of a ferroalloy, calcium carbide and sublimation of phosphorus into the gas phase.

Table 1. Effect of temperature on ΔG(kJ)*of $Ca_3(PO_4)_2$, SiO_2, Fe and C interaction

Reaction #	Temperature, ºC										
	1000	1200	1400	1600	1635.1	1692.4	1693.2	1702.8	1800	2000	2200
2	2022.4	1437.5	860.9	290.6	280.7	29.4	27.1	0	-272.9	-544.9	815.0
3	1777.9	1259.3	748.4	235.2	221.8	0	-2.0	-26.4	-272.8	-759.9	-1235.5
4	2059.3	1401.7	752.1	110.9	0	-180.6	-183.1	-213.0	-518.8	-1126.8	-1722.7
5	1748.8	1225.9	713.3	219.2	140.4	1.9	0	-13.6	-241.4	-638.8	-960.7

*- ΔGo was calculated using the Reactions Equation module of the HSC-10.0 software package [19]

The differential thermal analysis of the Chulaktau phosphorite used for the electric smelting is shown in Figure 1.
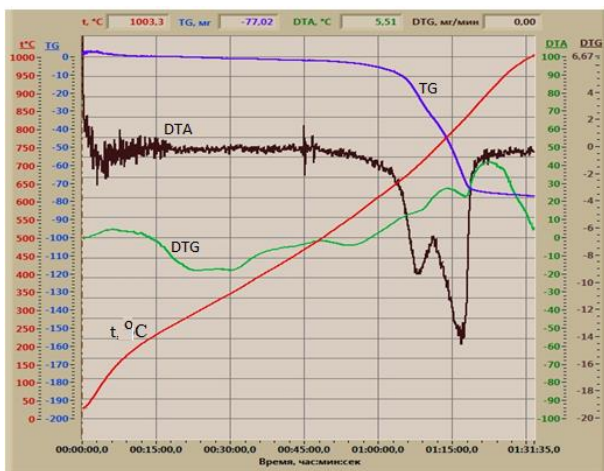

Figure 1. DTA of Chulaktau phosphorite

It can be seen that the heating is accompanied by two endothermic effects at temperatures of 674 and 838°C, which are associated with the decarbonization of $MgCO_3$ and $CaCO_3$. The phosphorite weight loss was 11.6%. The phosphorite after calcination at 950-960°C contained, wt %: 51.1 $Ca_3(PO_4)_2$; 25.59 SiO_2; 12.9 CaO; 1.8 MgO; 1.3 FeO; 0.91 Fe_2O_3; 1.7 Al_2O_3; 0.4 $CaSO_4$; 0.4 Na_2O; 0.6 K_2O; 0.1 TiO_2; 0.1 MnO; 2.7 CaF_2; 0.5 CO_2; 0.2 H_2O. The composition of steel shavings, wt %: Fe-97.6%, C-1.7%, Si-0.3%, Mn-0.2%, Cr-0.1, others-0.1%. The composition of coke, wt %: C-86.0; SiO_2-4.9; Fe_2O_3-2.2; CaO-1.5; Al_2O_3-1.8; MgO-0.4; S-0.8; H_2O-1.1; others-1.3. The composition of quartzite, wt %: SiO_2-97; CaO-0.7; Al_2O_3-0.8; Fe_2O_3-0.8; H_2O-0.1; others-0.3.

The studies included the process' computer thermodynamic modeling combined with mathematical planning of experiments, as well as the electric smelting of the phosphorite in an electric arc furnace.

The thermodynamic modeling was carried out using the HSC-10.0 Chemistry software package developed by Outokumpu Research Oy (Finland) [19]. The developers of the software package were based on the ideology of the SGTE (Scientific Group Thermodata Europe) consortium, which is engaged in the creation, support and distribution of high-quality databases designed to calculate the equilibrium composition of chemically reacting systems, as well as combining the efforts of researchers from different countries in order

to unify thermodynamic data and methods for obtaining them. The SGTE includes specialized research centers in Germany, Canada, France, Sweden, the UK and the USA. To calculate the equilibrium, we used in our work the Equilibrium Compositions subprogram of the HSC-10.0 software package, which is based on the minimum Gibbs energy principle. The equilibrium parameters of a thermodynamic system are determined by solving the mathematical problem of finding the extremum, considering all restrictions, using the Langrange functions and Newton's method of successive approximations. The calculation of the equilibrium distribution of elements was implemented according to the algorithm developed in M. Auezov South Kazakhstan University (Shymkent, Kazakhstan) [21]. The experiments were carried out at the installation shown in Figure 2.

The electric smelting of the charge was carried out in a single-electrode arc furnace (up to 15 kVA power) lined with chromium magnesite bricks. The bottom electrode was made of a graphite block. A graphite crucible (d=6 cm, h=12 cm) was placed on the hearth. The upper part of the furnace was closed with a removable cover with holes for the graphite electrode with diameter of 3 cm and gas outlet. The crucible was preliminarily heated by an arc for 20-25 min. After that, the first portion of the charge (200-250 g) was loaded into the crucible and melted for 3-6 minutes. Then, every 4-6 minutes, 100-150 g portions of the charge were added to the crucible. The total charge weight for 1 experiment was 700-1000 g. During the melting period, the current strength was 350-400A; the voltage was 30-35V. Electricity was supplied to the furnace from a TDZhF-1002 transformer. The required power was maintained by a thyristor regulator. After the end of the melting process, the furnace was cooled for 6-7 hours. The graphite crucible was removed from the furnace and broken. The resulting ferroalloy was weighed and analyzed to determine metals by the atomic absorption method using an AAS-1 instrument (Germany), as well as a JSM-6490LV scanning electron microscope with an INSA Energy energy-dispersive microanalysis system (Japan).

In addition, the silicon content in the alloy (Si(alloy), %) was determined on the basis of its density (D, g/cm3), which was found by the pycnometric method. Then the silicon content in the alloy was also calculated using the expression [22]:

$$Si_{(alloy)} = 252.405 - 101.848 \cdot D + 18.209 \cdot D^2 - 1.243 \cdot D^3 \qquad (6)$$
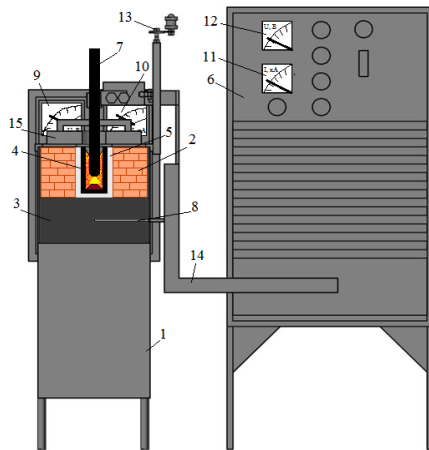
I-sketch

II – general appearance

Figure 2. Electrothermal installation for the phosphorite's electric smelting: 1 – furnace casing, 2 – chromium magnesite lining, 3 – carbon graphite hearth, 4 – graphite crucible, 5 – carbon graphite layer, 6 – transformer TDZhF-1002, 7 – graphite electrode, 8 – lower current supply, 9-12 – control ammeters and voltmeters, 13 – electrode movement mechanism, 14 – flexible part of the short network, 15 – furnace cover

The quality of the resulting calcium carbide and the content of the main substance (CaC_2) in it were determined by measuring its capacity – the volume of acetylene (dm^3) that is released during the interaction of 1 kg of calcium carbide with water.

To determine the optimal values of temperature and amount of iron, which ensure the maximum extraction of silicon from the phosphorite into the alloy, calcium into calcium carbide and phosphorus into the gas phase and production of commercial products, further studies included planning the experiments using the second-order rotatable designs (Box-Hunter plans) [23] with the construction of volumetric and planar images of the process parameters [24] followed by their geometric optimization. The independent factors in the study were the amount of steel shavings and the amount of coke (% of the phosphorite mass).

3. Results and discussion

Figures 3 and 4 show the effect of coke and steel shavings on the extraction degree (α, %) of silicon into the alloy, calcium into calcium carbide, and the concentration (C, %) of these metals in the resulting alloy and calcium carbide.
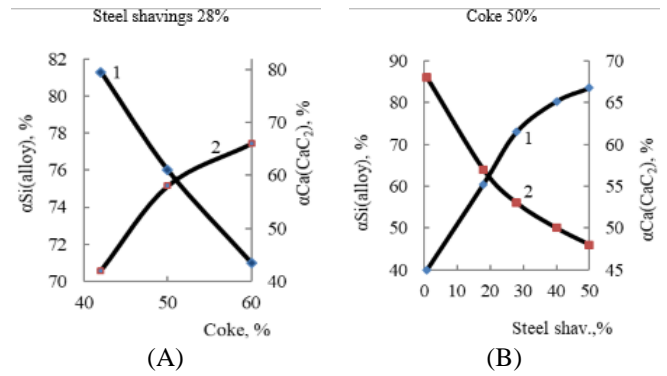

(A)   (B)

Figure 3. Effect of coke (a) and steel shavings (b) on the extraction degrees of silicon into the alloy and calcium into calcium carbide: 1-$\alpha_{Si(alloy)}$, %; 2-$\alpha_{Ca(CaC2)}$, %

It can be seen that at a constant amount of steel shavings (28%), an increase in the amount of coke leads to a decrease in $\alpha_{Si(alloy)}$ and a marked growth in $\alpha_{Ca(CaC2)}$ (from 40.3% at 42% of coke to 68.8% at 58% of coke). The decrease in $\alpha_{Si(alloy)}$ is associated with the development of the processes of formation of SiC and SiOgas, that is, with the loss of part of the silicon. The effect of the amount of steel shavings on the extraction degrees of silicon into the alloy and calcium into the calcium carbide is opposite: $\alpha_{Si(alloy)}$ increases with an increase in the amount of steel shavings, and $\alpha_{Ca(CaC2)}$ decreases.

The positive influence of steel shavings on $\alpha_{Si(alloy)}$ is explained by an increase in the solubility of silicon in iron with formation of liquid iron silicides. This increases the equilibrium shift of the reduction of silicon from silicon dioxide with carbon ($SiO_2 + 2C = Si + 2CO$) to the right.

(A)   (B)

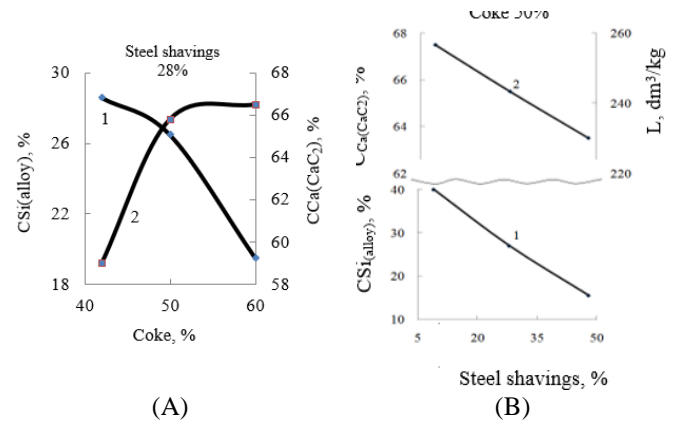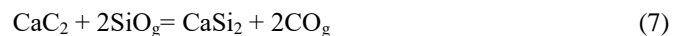*Figure 4. Effect of coke (A) and steel shavings (B) on the concentration of silicon in the alloy, calcium in the carbide and its capacity: 1-$C_{Si(alloy)}$, %; 2-$C_{Ca(CaC2)}$, %*

The decrease in the extraction level of calcium into CaC_2 with the increase in the amount of steel shavings is due to by-reactions in the bath, in particular, the reaction:

$$CaC_2 + 2SiO_g = CaSi_2 + 2CO_g \qquad (7)$$

This exothermic reaction is possible over a wide temperature range (Table 2).

The decrease in the thermodynamic probability of the reaction with increasing temperature, in accordance with the expression $\Delta G = \Delta H - T \cdot \Delta S$, is due to the fact that ΔH and ΔS become less negative (ΔG, ΔH and ΔS of the reaction were calculated using the Reactions Equation module of the HSC-10 software package [19]).

Table 2. Effect of temperature on ΔG, ΔH and ΔS of reaction 7

Reaction Equation					
$CaC_2+2SiO(g)=CaSi_2+2CO(g)$					
T	ΔH	ΔS	ΔG	K	Log K
°C	kJ	J/K	kJ		
300	-107.085	-47.925	-79.617	1.805E+007	7.257
500	-112.979	-56.198	-69.529	4.987E+004	4.698
700	-111.969	-55.053	-58.394	1.363E+003	3.135
900	-110.145	-53.361	-47.544	1.309E+002	2.117
1100	-107.476	-51.269	-37.076	2.573E+001	1.410
1300	-103.971	-48.893	-27.056	7.915E+000	0.898
1500	-99.653	-46.314	-17.532	3.285E+000	0.517
1700	-94.552	-43.592	-8.540	1.683E+000	0.226
1800	-91.719	-42.191	-4.250	1.280E+000	0.107

The silicon concentration in the ferroalloy decreases with an increase in coke in the charge, while the calcium concentration in CaC_2 increases (Figure 4). At an increase in the amount of steel shavings in the charge at a constant amount of coke (50%) the silicon concentration in the alloy, calcium concentration in the calcium carbide and calcium carbide capacity decrease, and most noticeably, the silicon concentration in the alloy (Figure 4).

Bearing in mind the opposite influence of steel shavings and coke on the extraction degrees of silicon and calcium into the target products and concentration of the metals in them, further studies were carried out by the experiment planning method with subsequent geometric optimization. Table 3 provides a matrix of the studies and their results.

Based on the results given in Table 3 according to [23], the following regression equations were obtained:

$$\alpha_{Si(alloy)} =104.9+3.23\cdot St-2.91\cdot C-27.63\cdot 10^{-3}\cdot St^2+24.93\cdot 10^{-3}\cdot C-10.84\cdot 10^{-3}St\cdot C \tag{8}$$

$$\alpha_{Ca(CaC2)}=-64.03+0.22\cdot St+2.96\cdot C+8.68\cdot 10^{-3}\cdot St^2-4.68\cdot 10^{-3}\cdot C2+2.32\cdot 10^{-3}St\cdot C \tag{9}$$

$$C_{Si(alloy)}=35.16-0.76\cdot St+0.65\cdot C+6.97\cdot 10^{-3}\cdot St^2-8.92\cdot 10^{-3}\cdot C^2-2.23\cdot 10^{-3}St\cdot C \tag{10}$$

$$C_{Ca(CaC2)}=59.37-0.45\cdot St+4.83\cdot C+13.77\cdot 10^{-5}\cdot St^2-45.5\cdot 10^{-3}\cdot C^2+7.01\cdot 10^{-3}St\cdot C \tag{11}$$

$$L=-301.25-1.80\cdot St+21.19\cdot C+3.57\cdot 10^{-5}\cdot St^2-0.20\cdot C^2+2.86\cdot 10^{-3}St\cdot C \tag{12}$$

Table 3. Effect of coke and steel shavings on the technological parameters of the phosphorite's electric smelting

#	Variables				$\alpha Si_{(alloy)}$,%	$\alpha Ca_{(CaC2)}$,%	$CSi_{(alloy)}$,%	$C_{Ca(CaC2)}$,%	L, dm³, kg
	Coded appearance		Natural appearance						
	X_1	X_2	St, %	C, %					
1	-1	-1	14	44.4	56.0	49.2	34	64	238
2	+1	-1	42	44.4	90.2	42	22.6	59.4	220
3	-1	+1	14	55.6	51.7	72.3	31.8	68	253
4	+1	+1	42	55.6	82.5	58.1	19.7	65.6	244
5	+1.414	0	48	50	88.2	49.6	18.9	63.3	237
6	-1.414	0	8	50	43.3	66.8	41.1	67	249
7	0	+1.414	28	58	71	70.3	23.8	66.3	246
8	0	-1.414	28	42	85.3	38.7	29.6	58.4	215
9	0	0	28	50	74	53.6	26.8	65.5	244
10	0	0	28	50	76	55	26	65.6	245.5
11	0	0	28	50	76.2	54.3	27	65.15	243
12	0	0	28	50	75.8	54.8	25.6	65.3	243.2
13	0	0	28	50	76.3	53.9	27.6	65.72	245

Values of the tabular Fisher criterion (F_{tab}) for the confidence level ≥95% and the calculated Fisher criteria (F_{calc}) are shown in Table 4.

Table 4. Tabular and calculated Fisher criterion values for equations 8-12

F_{tab}	6.59	6.59	6.59	6.59	6.59
F_{calc}	Equation 8 =5.78	Equation 9 =6.38	Equation 10 =6.52	Equation 11 =6.39	Equation 12 =6.54

It follows from Table 4 that $F_{tab}>F_{calc}$ for all regression equations. Therefore, in accordance with [23], all these equations are adequate. Based on equations 8-12 according to [24], we built volumetric and planar images of changing the process parameters depending on the amount of steel shavings and coke (Figure 5, 6).

The highest extraction degree of silicon into the alloy (92%) was achieved in the presence of the maximum amount of steel shavings (48%) and the minimum amount of coke (42%). On the contrary, the maximum $C_{Ca(CaC2)}$ (84.2%) was achieved when the smelting of the charge containing the minimum amount of steel shavings (8%) and maximum amount of coke (58.0%). The silicon concentration in the

alloy varied from 18.8 to 40.6% (8% of steel shavings and 42% of coke). The resulting alloy in terms of silicon content is FS15 ferrosilicon (tpf area in Figure 5-III), FS25 ferrosilicon (tfzor area in Figure 5-III) and FS45 ferrosilicon (kxd area in Figure 5-III). The 3rd grade calcium carbide was formed in the lghd area (Figure 6), and the 2nd grade one – in the jygl region (Figure 6).

One of the effective and efficient methods for determining the optimal parameters for processes with a large number of output parameters is the geometric optimization method, which we have used repeatedly for various systems [25,26]. The method consists in superimposing the patterns of output parameters on top of each other; and, taking into account the accepted assumptions, the optimal values of the independent factors (in our case, the amount of coke and steel shavings) are determined, that provide the accepted levels of output parameters: $\alpha_{Si(alloy)}$, $\alpha_{Ca(alloy)}$, $C_{Si(alloy)}$, $C_{Ca(CaC2)}$, L_{CaC2}. Combining the output parameters with the condition that $\alpha_{Si(alloy)}$ =70-80%, $\alpha_{Ca(alloy)} \geq 60\%$, $C_{Si(alloy)} \leq 20\%$ is shown in Figure 7 and Table 5. The abcde area corresponds to the set conditions regarding $\alpha_{Si(alloy)}$, $\alpha_{Ca(alloy)}$ and $C_{Si(alloy)}$.

A   B
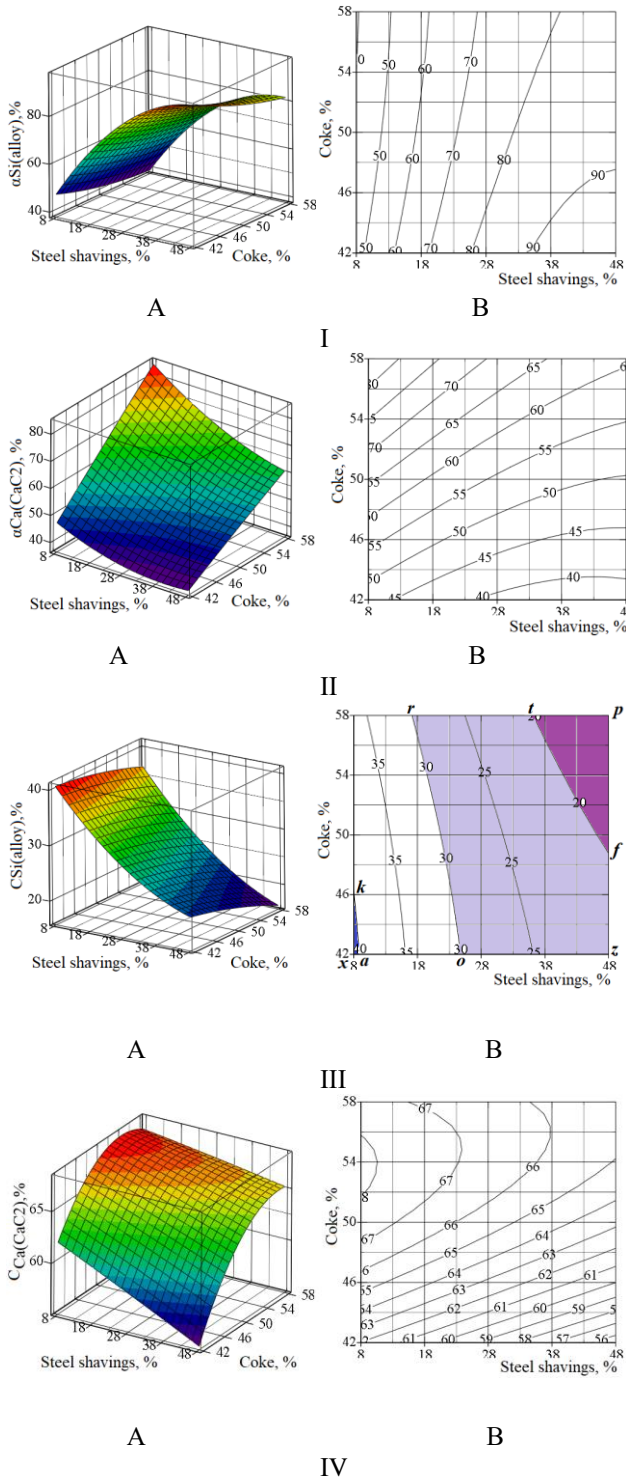
I

A   B

II

A   B

III

A   B

IV

Figure 5. Effect of coke and steel shavings on $\alpha_{Si(alloy)}$, $\alpha_{Ca(CaC2)}$, $C_{Si(alloy)}$, $C_{Ca(CaC2)}$ during the phosphorite's electric smelting (A – Volumetric image, B – Planar image): I – $\alpha_{Si(alloy)} = f(C, St)$, II – $\alpha_{Ca(CaC2)} = f(C, St)$, III - $C_{Si(alloy)} = f(C, St)$, IV - $C_{Si(alloy)} = f(C, St)$

It follows from Table 5 and Figure 8 that in order to produce FS25 grade ferrosilicon containing 20-30% of silicon and calcium carbide with a capacity of 245.1-248.1 dm³/kg (2nd grade), the smelting process should be carried out in the presence of 52-58% of coke and 24.4-38% of steel shavings. In this case, the extraction degree of silicon into the ferroalloy was 70-80%, and calcium into calcium carbide – 60-70%.
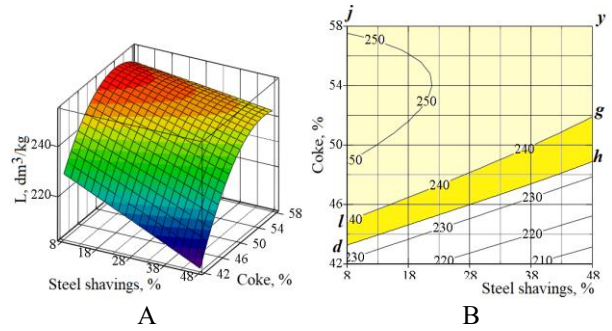

A   B

Figure 6. Effect of coke and steel shavings on L=f(C, St) during the phosphorite's electrosmelting. A – Volumetric image, B – Planar image
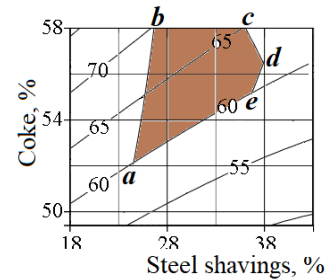

Figure 7. Combined information on the effect of coke and steel shavings on the technological parameters of phosphorite's electric smelting. Lines: ab-$\alpha_{Si(alloy)}$=70%; ed- $\alpha_{Si(alloy)}$=80%; ae - $\alpha_{Ca(CaC2)} \geq 65\%$; cd - $C_{Si(alloy)} \geq 20\%$

Table 5. Values of variables and output parameters in the abcde area of Figure 7

Point in Fig. 7	Variables		Output process parameters				
	Steel shavings, %	Coke, %	$\alpha_{Si(alloy)}$, %	$\alpha_{Ca(CaC2)}$, %	$C_{Si(alloy)}$, %	$C_{Ca(CaC2)}$, %	L, dm³/kg
a	24.4	52.0	70.0	60.0	30.0	66.7	248.1
b	26.6	58.0	70.0	70.0	24.4	66.6	247.7
c	35.9	58.0	77.8	65.0	20.0	65.9	245.1
d	38.0	56.6	80.0	61.9	20.0	66.0	245.5
e	36.6	55.2	80.0	60.0	24.1	66.0	245.5

4. Conclusions

Based on the electric smelting of Chulaktau phosphorite mixed with coke and steel shavings in an arc furnace, the following conclusions can be drawn:

1. From the thermodynamic point of view, the joint formation of iron silicides, gaseous phosphorus and calcium carbide from $Ca_3(PO_4)_2$-SiO_2-C-Fe systems is possible at a temperature of above 1635-1702ºC.

2. With a constant amount of coke, an increase in the amount of steel shavings in the charge increases the extraction degree of silicon into the alloy and decreases the extraction degree of calcium into calcium carbide. An increase in the amount of coke in the charge at a constant amount of steel shavings leads to an increase in the extraction degree of calcium into CaC_2 and silicon into the alloy.

3. Based on the obtained volumetric and planar images of the coke and steel shavings effect on the technological parameters of the phosphorite's electric smelting, it was found that in order to produce FS25 grade ferrosilicon containing 20-30% of Si and calcium carbide with a capacity of 245.1-248.1 dm³/kg (2nd grade), the process should be carried out in

the presence of 52-58% of coke and 24.4-38% of steel shavings. In this case, the extraction degree of silicon into the ferroalloy was 70-80%, and calcium into calcium carbide – 60-70%.

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Ферроқорытпалар, кальций карбиді және фосфордың сублимациясы өндірісімен фосфориттердің электрлік балқуы

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Аңдатпа. Мақалада Қаратау бассейнінің Чулақтау кен орнындағы фосфориттердің кокс пен болат жоңқаларымен өзара әрекеттесуін зерттеу нәтижелері келтірілген. Зерттеулер HSC-10 бағдарламалық кешенін пайдалана отырып, компьютерлік термодинамикалық модельдеу әдістерімен эксперименттерді математикалық жоспарлаумен, сондай-ақ электр доғалы пеште фосфори балқыту әдісімен жүргізілді. Жүргізілген зерттеулер негізінде $Ca_3(PO_4)_2$-SiO_2-C-Fe жүйелерінің аралық өнімдерінің бірлескен түзілуі 1635-1702ºC температурада мүмкін екендігі анықталды. Фосфоритті электрмен балқытудың технологиялық параметрлеріне кокс пен болат жоңқаларының әсері нәтижесінде алынған көлемді және жазықтық бейнелер негізінде құрамында 20-30% Si және кальций карбиді бар, өнімділігі 245.1-248.1 дм³/кг (2-ші сорт) болатын FS25 маркалы ферросилицийді алу үшін процессті 52-58% кокс және 24.4-38% болат жоңқалары бар болғанда жүргізу керек. Бұл жағдайда ферроқорытпаға кремнийді алу дәрежесі 70-80%, ал кальций карбидіне кальций алу дәрежесі 60-70% құрады.

Негізгі сөздер: фосфорит, термодинамикалық модельдеу, электр балқыту, кальций карбиді, ферроқорытпалар.

Электрическое плавление фосфоритов с производством ферросплава, карбида кальция и сублимацией фосфора

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Аннотация. В статье представлены результаты исследования взаимодействия фосфоритов Чулактауского место-рождения бассейна Каратау с коксом и стальной стружкой. Исследования проводились методами компьютерного термодинамического моделирования с использованием программного комплекса HSC-10 совместно с математическим планированием экспериментов, а также методом электроплавки фосфорита в электродуговой печи. На основании проведенных исследований установлено, что совместное образование промежуточных продуктов систем $Ca_3(PO_4)_2$-SiO_2-C-Fe возможно при температуре > 1635-1702ºC. На основании полученных объемных и плоскостных изображений влияния кокса и стальной стружки на технологические параметры электроплавки фосфорита установлено, что для получения ферросилиция марки FS25, содержащего 20-30% Si и карбида кальция, производительностью 245.1-248.1 дм³/кг (2-й сорт), процесс следует проводить при наличии 52-58% кокса и 24.4-38% стальной стружки. При этом сте-пень извлечения кремния в ферросплав составила 70-80%, а кальция в карбид кальция – 60-70%.

Ключевые слова: фосфорит, термодинамическое моделирование, электроплавка, карбид кальция, ферросплавы.