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ACTA METALLURGICA SLOVACA

2025, VOL. 31, NO. 2, 66-73

RESEARCH PAPER

Theoretical and experimental assessment of the feasibility of producing ferroalloy from lead-zinc ores and leaching cakes of vanadium-containing quartzites

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Received: 19.03.2025,
Accepted: 07.04.2025

ABSTRACT

The article provides the findings of both theoretical and experimental investigations aimed at identifying the optimal process parameters that maximize the extraction of silicon and non-ferrous metals from a mixture of sulfide ore and sulfuric acid leaching cakes of vanadium-containing quartzites. This process results in the production of a ferroalloy and sublimates enriched with zinc and lead. Utilizing a method of computer thermodynamic modelling to predict the minimization of Gibbs free energy, the effect of the quantities of coke and steel chips on the silicon extraction into the ferroalloy and zinc and lead into the sublimates was analysed. The optimal processing parameters for the ore and cake mixture through electric smelting were established using the second-order rotatable designs (Box-Hunter Design) within a single-electrode arc furnace. Under equilibrium conditions in the examined system, with 18% steel chips and an augmentation of coke from 20 to 25%, the silicon extraction degree into the alloy escalates from 62.95% to 70.98%. With 23% coke and a variation in steel chips quantity from 6% to 30%, the silicon extraction degree into the alloy increases by 13.79%, from 59.97% to 73.76%. Ferrosilicon of the FeSi45 grade – yielding the extraction degree of 64.2% to 73.1% Si – is formed in the presence of 8.8% to 19.3% steel chips and 18.0% to 26.0% coke, while the FeSi50 grade – yielding the extraction degree of 62.5% to 67.3% – is achieved with 6.0% to 11% steel chips and 18% to 26% coke. During the electric smelting of a mixture comprising 12% magnetite concentrate and 22% coke, three grades of ferrosilicon were produced: FeSi25 (with 30% steel chips), FeSi45 (with 18% steel chips), yielding the silicon extraction degree of 72.4% to 80.6%, and FeSi50 (with 6% steel chips) with the silicon extraction degree of 69.3% to 74.5%. Furthermore, 98.2% to 98.6% of these metals are extracted into sublimates containing 25.2% zinc and 13.7% lead.

Keywords: lead zinc ore; leach cake; vanadium quartzites; electric smelting; ferrosilicon

INTRODUCTION

Kazakhstan has several large deposits of silica-containing ores, including quartzites from the Balasauskandyk, Kurumsak, and Dzhebagly deposits. However, using this raw material for ferrosilicon production is impractical since these ores are complex and contain, in addition to 72.5% SiO_2 and 0.8-1.2% V_2O_5, about 0.3% molybdenum, 0.2-0.5% uranium, and 0.05-0.15% rare earth metals [1]. Various methods are used for processing this category of ores, mainly associated with metal extraction through acid (autoclave, tank, or heap) or alkaline leaching, followed by extracting valuable components from the solution [2-6]. Combined methods are also used, incorporating different techniques, such as sulfuric acid and alkaline leaching, a pyro-hydrometallurgical method, and the chlorine method [7-14]. Despite its efficiency, the hydrometallurgical processing of ores inevitably results in the formation of significant amounts of wastes (up to 85-90% of the initial raw material mass) in the form of leaching cakes. These cakes contain up to 80% SiO_2, 15-16% C, and 0.08-0.1% V. The presence of silica and carbon in the cakes presents a fundamental opportunity to use these wastes in producing silicon-containing ferroalloys as a substitute for quartzite and a partial replacement for carbonaceous reductants [15].

At M. Auezov South Kazakhstan University, in collaboration with the National Center for Complex Processing of Mineral Raw Materials of the Republic of Kazakhstan, work is underway to develop a technology for the comprehensive processing of sulfide lead-zinc ores using a novel method that eliminates concentrate production and roasting [16-18]. This technology allows for the simultaneous production of zinc concentrate (23.5-34.0% Zn and 9.15-15.2% Pb) and standard-grade silicon-containing ferroalloys. The SiO_2 content in the sulfide ore used is 40-47%. The grade of ferrosilicon obtained from it does not exceed FeSi45 (41-44% Si). The ferrosilicon grade can be increased if the charge contains a higher SiO_2 content. To achieve this, the raw material in the charge must include more of this oxide. It is assumed that using a charge with a higher SiO_2 content, following the chemical kinetics equation $V=K\cdot S\cdot C^n$ [19] (in this case, $V=K\cdot S(\text{carbon})\cdot C^n(SiO_2)$, where V is the rate constant, K is the rate constant, S(carbon) is the surface area of carbon particles, and C SiO_2 is the concentration of SiO_2 in the reaction zone), will increase the rate of ferrosilicon formation.

This article presents the results of theoretical and experimental studies aimed at determining the optimal process parameters that ensure maximum silicon extraction into the alloy from a mixture of lead-zinc sulfide ore and leaching cakes of vanadium-containing quartzites, with the production of ferroalloy and the extraction of zinc and lead into sublimates.

MATERIAL AND METHODS

The research used a mixture of sulfide lead-zinc ore from the Shalkiya deposit and a leaching cake of vanadium-containing quartzites of the Balasauskandyk deposit in a 1:1 ratio. The chemical composition of the materials used in the study is as follows:

- Sulfide ore of the Shalkiya deposit (hereinafter referred to as SO), wt.%: 46.3 SiO_2, 12.4 CaO, 8.1 MgO, 7 $CaSO_4$, 6.9 Al_2O_3, 5.9 ZnS, 3.6 FeS, 2.8 FeO, 2.7 Fe_3O_4, 2.6 Fe_2O_3, 1.5 PbS, 0.2 TiO_2;
- Leaching cake of vanadium-containing quartzites of the Balasauskandyk deposit (hereinafter referred to as LC), wt.%: 72.5 SiO_2, 19 C, 3.00 H_2O, 1.5 CaO, 1.4 Fe_2O_3, 1.3 Al_2O_3, 0.7 MgO, 0.15 BaO, 0.15 V_2O_5;
- Magnetite concentrate of LLP "Iron Concentrate Company" (hereinafter referred to as MC), wt.%: 85.9 Fe_3O_4, 9 SiO_2, 2 CaO, 1.4 Al_2O_3, 0.4 MgO, 0.4 PbO, 0.3 MnO, 0.3 K_2O, 0.2 Na_2O, 0.2 ZnO;
- Coke, wt.%: 86.3 C, 4.9 SiO_2, 2.2 Fe_2O_3, 1.8 Al_2O_3, 1.5 CaO, 0.4 MgO, 1.1 H_2O, 1 CH_4, 0.8 CaS;
- Steel chips of carbon steel (hereinafter referred to as SC), wt.%: 94.33 Fe, 1.67 C, 1.67 Si, 1.33 Mn, 0.67 Cr, 0.33 Al.

The HSC-6.0 software package, developed by Outokumpu (Finland), was used for thermodynamic prediction of ferrosilicon production and zinc and lead extraction. The equilibrium composition of the studied systems was calculated using the Equilibrium Compositions module included in the HSC-6.0 [20]. The algorithm for calculating the equilibrium distribution of elements was developed by specialists from Metallurgy Department of M. Auezov South Kazakhstan University [21]. Thermodynamic modeling was carried out in the temperature range of 500 to 2000°C at a pressure of 1 bar.

The optimization of electric smelting parameters was conducted using the method of second-order rotatable designs (Box-Hunter Design) [22, 23]. This method allows for developing adequate mathematical models [24] describing the dependence of optimization parameters on independent factors with a relatively small number of experiments. For a two-factor experiment, the number of trials (N) is calculated using the formula:

$$N=2k+2\times k+2k+1, \quad (1)$$

where k is the number of independent factors, 2k is the number of trials in the core of the plan, 2k is the number of star-point trials (where the star-point value α is determined by the expression ±α=2k/4), and 2k+1 is the number of trials at the center of the plan. For the planned two-factor experimental series, the number of trials was:

$$N=22+2\times 2+2\times 2+1=13. \quad (2)$$

The confidence limit for determining the adequacy of the regression equations was 95%. Using the MathCAD software [24, 26], the obtained equations enabled the creation of three-dimensional and planar models that illustrate the relationship between process parameters and independent factors. The optimal process parameters were identified by overlaying planar optimization parameter images.

Experiments on smelting the SO and LC mixture were conducted in a single-electrode arc furnace.

The laboratory single-electrode arc furnace had a chromium-magnesite lining and a bottom made of a carbon-graphite block. A graphite crucible (6 cm in diameter, 16 cm in height) was placed on the graphite block. The space between the crucible and the lining was filled with graphite granules (fraction size 0.1-0.3 cm) to improve thermal insulation and ensure uniform temperature distribution. The upper current conductor, made of a graphite electrode (3 cm in diameter), was connected to a mechanical positioning system. A single-phase furnace transformer TDJF-1002 supplied power to the furnace with a thyristor power regulator. The furnace was covered with a removable refractory lid from the top.

Before smelting, the furnace was preheated by an arc for 35-40 minutes at a 35-40 V voltage and a 200-400 A current. Then, the first charge batch (200-250 g) was loaded into the furnace. After smelting, subsequent charge batches were added and melted at intervals of 7-12 minutes. The total smelting duration, at a voltage of 25-35 V and a current of 300-450 A, was 40-45 minutes from the moment of charge loading. After smelting, the crucible with the products was cooled in the furnace for 3-3.5 hours and then in the air for 2-3 hours. The cooled crucible was broken apart, separating the products into alloy and slag.

The composition of raw materials and smelting products was analyzed using the following methods: Atomic Absorption Spectroscopy (AAS-1, Germany), Scanning Electron Microscopy with Energy Dispersive Analysis (JSM-6490LV with INSAEnergy, Japan). Silicon content in the alloy was determined according to State Standard 13230.1-93 [27] and by measuring the ferrosilicon density. The silicon extraction degree in the alloy (αSi (alloy), %) was calculated as the ratio of silicon mass transferred to the metal phase to the silicon mass in the charge.

The zinc extraction degree into sublimates (%) was calculated using the formula:

$$\alpha_{Zn} = \frac{G_{Zn(charge)} - G_{Zn(alloy)} - G_{Zn(slag)}}{G_{Zn(charge)}} \cdot 100 \quad (3)$$

where: $G_{Zn(charge)}$, $G_{Zn(alloy)}$, $G_{Zn(slag)}$ are the masses of zinc in the charge, alloy, and slag, respectively.

A similar formula was used to calculate the degree of lead extraction into sublimates.

RESULTS AND DISCUSSION

Initially, the optimal equilibrium conditions for obtaining a silicon-containing alloy and the sublimation of Zn and Pb from the SO-LC-MC-coke-SC system (SO:LC=1:1) were determined. Magnetite concentrate (MC) was partially used to replace the iron from steel chips and enhance the extraction of zinc and lead into the gas from sulfide ore. So, ΔG°=0 for the reduction of zinc from ZnS in the presence of Fe3O4, calculated using the Reaction Equations module of the HSC-6.0 software [20], for the reaction:

$$ZnS+Fe_3O_4+2C=Zn(gas)+3Fe+2CO+SO_2; \quad (4)$$

is observed at 1205.8 °C, whereas ΔG°=0 for the reduction of zinc in the absence of Fe_3O_4, according to the reaction:

$$ZnS+C=Zn(gas)+CS_2; \quad (5)$$

occurs only at a temperature of 1619.7 °C.

Fig. 1 illustrates the effect of temperature on the equilibrium distribution (α, %) of silicon in the system at 12% MC, 23% coke, and 18% SC. It can be seen that FeSi formation begins at 1300°C. The maximum silicon extraction degree into the elemental state (19.8%) occurs at 1800°C. The decrease in the silicon extraction in FeSi and in its elemental state is associated with an increased degree of silicon transition into gaseous SiO (19.4% at 1800°C and 45.7% at 2200°C). In the system, silicon also partially forms the following compounds: Fe_3Si, $FeSi_2$, $FeSi_{2.33}$, Fe_5Si_3, VSi_2, CrSi.

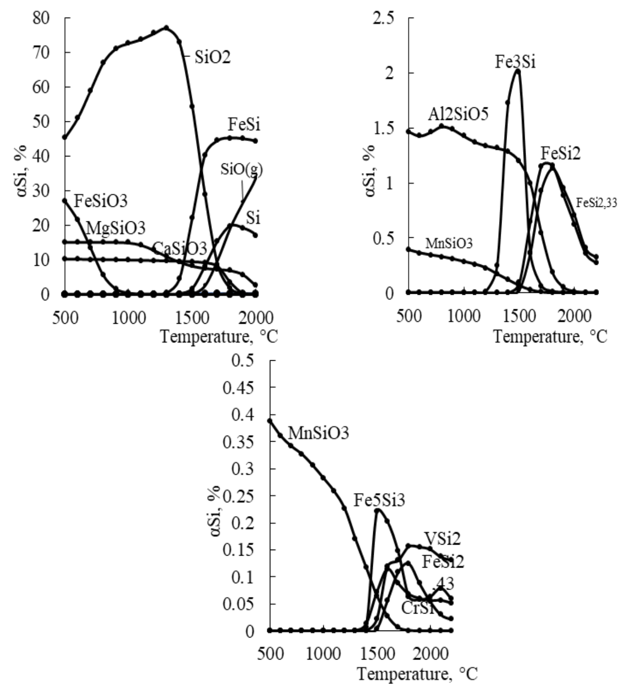


Fig. 1 Effect of Temperature on the Equilibrium Distribution of Silicon

Fig. 2 shows that zinc transitions into the gas at temperatures above 900°C. At ≥1700°C, this transition exceeds 99%. A noticeable transition of lead into the gas occurs at temperatures above 1200°C, reaching a maximum (96.64%) at 2000°C.

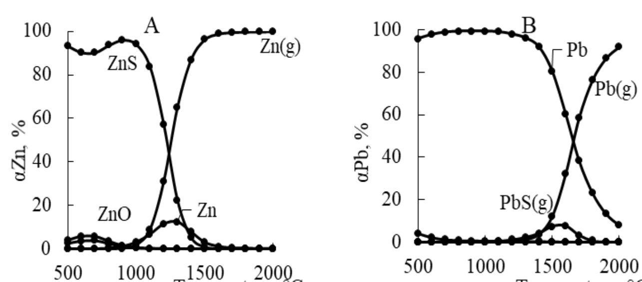


Fig.2 Effect of temperature on the equilibrium distribution of Zinc (A) and Lead (B)

Fig. 3 illustrates the extraction degrees of elements into the alloy and the gas phase.

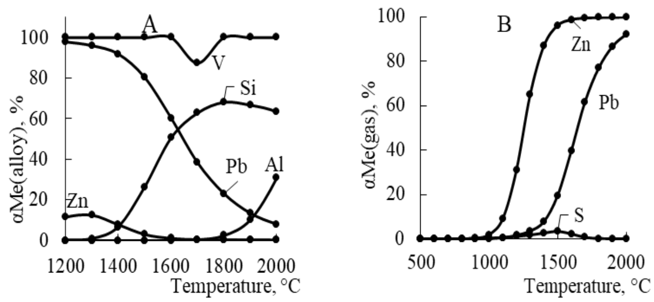


Fig. 3 Effect of Temperature on the Extraction Degree of Elements into the Alloy (A) and the Gas Phase (B)

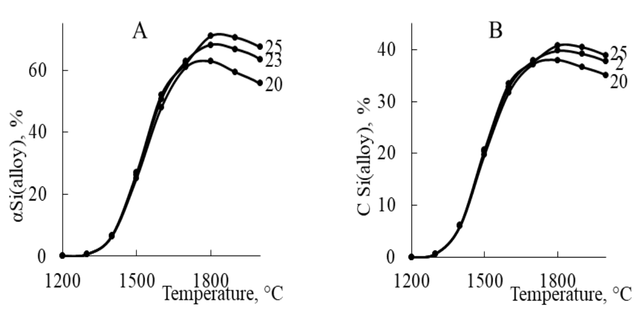
The highest silicon extraction degree into the alloy (69.08%) – as the sum of its extraction into Si and iron silicides – occurs at 1800°C. At this temperature, the zinc extraction into the alloy is 0.29%, lead is 23.08%, and vanadium is nearly 100%. Zinc is extracted into the gas more completely than lead. Aluminum begins to reduce at 1800°C. At 2000°C, the aluminum reduction degree and its transition into the alloy reaches 30.8%. All vanadium transfers into the alloy at temperatures ≥1800°C.

Table 1 presents the elemental concentrations in the alloy. The maximum silicon content in the alloy (39.79%) is observed at 1800°C (close to the lower Si concentration in ferrosilicon of the FeSi45 grade (41%).

Table 1 Effect of Temperature on the Elemental Composition of the Alloy, %

Elements	Temperature, °C								
	1400	***1500***	***1600***	***1700***	***1800***	***1900***	***2000***	***2100***	***2200***
Al	0	0	0	0.02	0.13	0.53	1.6	3.2	2.95
Fe	90.36	77.05	65.35	60.8	59.05	59.44	60.09	62.01	62.9
Pb	2.04	1.48	0.94	0.55	0.32	0.19	0.11	0.07	0.05
Si	6.09	20.32	32.78	37.82	39.79	39.23	37.68	34.26	33.67
V	0.14	0.12	0.1	0.08	0.09	0.09	0.09	0.09	0.1
Zn	0.5	0.16	0.05	0.02	0.01	0.01	0	0	0

A study was conducted on the effect of temperature and coke on the silicon extraction into the alloy (in the form of Si and iron silicides) – αSi(alloy), as well as on its concentration in the alloy – CSi (alloy) (**Fig. 4**). In this series of experiments, the composition included: steel chips (SC) – 18%, magnetite concentrate (MC) – 12%, coke content varied from 20% to 25% of the total mass of ore and cake mixture.



Numbers on the lines – Carbon quantity, %

Fig. 4 Effect of Temperature and Coke on Silicon Extraction into the Alloy (A) and Silicon Concentration in the Alloy (B)

As the coke content increases, αSi(alloy) rises from 62.95% to 70.98% at 1800°C. The silicon concentration in the alloy also increases from 37.95% to 41%. The decrease in the extraction degree and concentration of this element in the alloy at temperatures ≥1800°C is associated with the formation of gaseous SiO, into which, for example, at 1900°C, 23.6-32.29% of silicon is extracted.

Table 2 and **Table 3** present the effect of temperature and coke content on the extraction of zinc and lead into the gas phase.

Table 2 Effect of Temperature and Coke on the Zinc Extraction into the Gas Phase

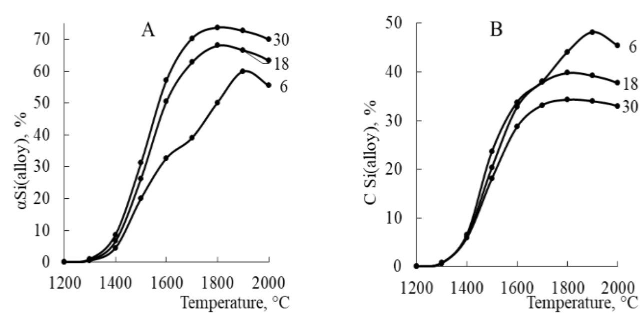
Coke quantity, %	Temperature, °C												
	800	***900***	***1000***	***1100***	***1200***	***1300***	***1400***	***1500***	***1600***	***1700***	***1800***	***1900***	***2000***
20	0.02	0.29	1.98	9.47	31.82	65.74	87.45	96.36	98.84	99.52	99.75	99.85	99.90
25	0.02	0.26	1.78	8.71	30.45	64.40	86.59	96.02	98.70	99.48	99.69	99.80	99.87

Table 3 Effect of Temperature and Coke on the Lead Extraction into the Gas Phase

Coke quantity, %	Temperature, °C											
	900	***1000***	***1100***	***1200***	***1300***	***1400***	***1500***	***1600***	***1700***	***1800***	***1900***	***2000***
20	0.03	0.15	0.57	1.67	3.76	8.36	21.00	42.43	63.84	79.14	88.43	92.99
25	0.03	0.14	0.55	1.56	3.42	7.44	18.55	37.86	60.96	75.35	85.25	91.28

Table 2 and **Table 3** show that the quantity of coke almost does not affect the zinc extraction into the gas. On the contrary, up to 2000°C, an increase in coke quantity reduces the lead extraction into the gas. In the 1000-2000°C temperature range, zinc is extracted more efficiently than lead.

When studying the effect of steel chips (SC) content from 6% to 30% on equilibrium process parameters, the coke content was 23%, and magnetite concentrate (MC) was 12%. The research results are presented in **Fig. 5**.



Numbers on the lines – steel chips quantity, %

Fig. 5 Effect of Temperature and Steel Chips on Silicon Extraction (A) and Silicon Concentration (B) in the Alloy

Fig. 5 shows that changes in steel chips (SC) quantity significantly affect process parameters. The silicon extraction into the alloy increases by 13.79% as SC content rises, and the silicon concentration in the alloy decreases by 13.88%. The maximum silicon extraction into the alloy (73.76%) is observed at 1800°C and 30% SC, whereas the highest silicon concentration in the alloy (44.06%) is achieved at 6% SC. The zinc extraction into the gas phase changes insignificantly with increasing SC quantity (**Table 4**). Regardless of the SC quantity, the zinc extraction exceeds 99% at temperatures ≥1700°C. The lead extraction degree decreases as the SC content in the charge increases; for example, at 1900°C, it drops from 82.0% to 75.4% (**Table 5**).

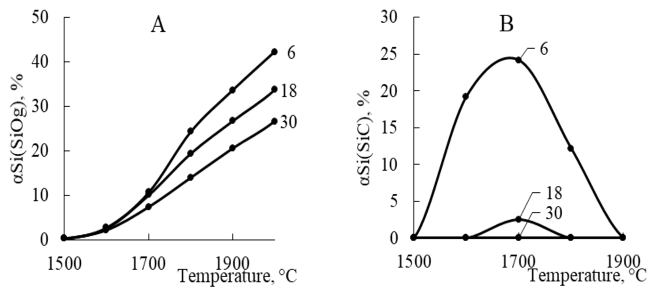
Table 4 Effect of Temperature and Steel Chips on the Zinc Extraction into the Gas Phase

Steel chips quantity, %	Temperature, °C									
	1300	***1400***	***1500***	***1600***	***1700***	***1800***	***1900***	***2000***	***2100***	***2200***
6	64.4	86.8	95.9	99.1	99.7	99.8	99.8	99.9	99.9	100.0
30	64.9	86.9	96.3	98.8	99.5	99.7	99.8	99.9	99.9	99.9

Table 5 Effect of Temperature and Steel Chips on the Lead Extraction into the Gas Phase

Steel chips quantity, %	Temperature, °C									
	1300	*1400*	*1500*	*1600*	*1700*	*1800*	*1900*	*2000*	*2100*	*2200*
6	2.1	4.3	8.4	18.8	48.9	72.7	82.0	87.5	92.9	95.9
30	1.3	3.0	7.3	19.6	40.2	59.8	75.4	85.4	90.9	94.4

Increasing SC content reduces the silicon transition into SiOg and SiC (**Fig. 6**). At 6% SC and 2000°C, the silicon transition into SiOg is 42.8%, whereas at 30% SC, it decreases to 27.8%. The silicon transition into SiC at 1700°C decreases from 24.15% to <0.1%.



Numbers on the lines – Steel chips quantity, %

Fig.6 Effect of Temperature and Steel Chips on Silicon Extraction into SiOg (A) and SiC (B)

An increase in SC content enhances the silicon extraction from SiO_2 into FeSi. This process reduces the quantity of SiO_2 available for forming gaseous SiO, lowering the silicon transition from SiO_2 to SiO.

The decrease in the silicon transition into SiC with increasing iron content in the charge is because iron can break down SiC according to the reaction: mFe+nSiC=FemSin+nC [28-32]. The ΔG° calculation, performed using the Reaction Equations module of the HSC-6.0, showed that at 1700°C, the Gibbs free energy for the reaction: Fe+SiC=FeSi+C is -22.2 kJ, while for the reaction: $5Fe+3SiC=Fe_5Si_3+3C$ ΔG°=-90.3 kJ. The thermodynamic calculations confirm that as the Fe/Si ratio increases, the likelihood of SiC decomposition also increases. Given the opposing effects of SC content on the silicon extraction into the alloy and its concentration in the alloy, the determination of optimal equilibrium process parameters for temperature and SC content was conducted using the method of second-order rotatable designs. During these experiments, the coke (23%) and magnetite concentrate (12%) contents remained constant, and the SO:LC ratio was 1:1. The effect of temperature and steel chips on αSi(alloy) and CSi(alloy) was studied within the variable ranges shown in **Table 6**. The experimental design matrix and results are presented in **Table 7**.

Table 6 Factor Levels and Variation Ranges for Studying the Effect of Temperature and Steel Chips on the Interaction of Shalkiya Ore and Leaching Cakes of Vanadium-Containing Quartzites

Variables	Coded designation	Natural form	
		T, °C	*SC, %*
Basic level	0	1800	18
Variation range	Δ	141.5	8.5
Upper level	+1	1941.5	26.5
Lower level	-1	1658.5	9.5
Upper star-point	+1.414	2000	30
Lower star-point	-1.414	1600	6

Table 7 Experimental Design Matrix and Results

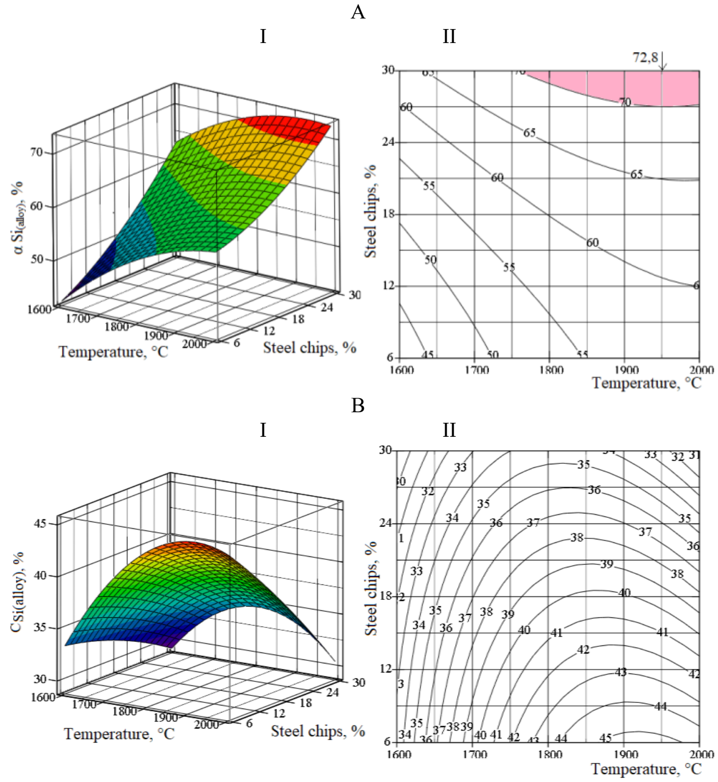
№	Variables				Process parameters			
	Coded kind		*Natural kind*		*αSi(alloy) studied, %*	*αSi(alloy) calculated, %*	*C Si(alloy), studied, %*	*CSi(alloy), calculated, %*
	X1	*X2*	*T, °C*	*SC, %*				
1	-1	-1	1658.5	9.5	47.3	48.1	36.0	36.8
2	+1	-1	1941.5	9.5	57.5	58.5	44.0	43.8
3	-1	+1	1658.5	26.5	62.9	62.2	32.2	32.8
4	+1	+1	1941.5	26.5	70.0	69.5	35.2	34.8
5	1.414	0	2000	18	63.4	63.1	37.7	38.2
6	-1.414	0	1600	18	50.6	50.6	32.8	31.9
7	0	1.414	1800	30	70.3	71.2	34.5	34.4
8	0	-1414	1800	6	54.6	53.4	44.0	43.7
9	0	0	1800	18	60.0	60.1	39.8	39.7
10	0	0	1800	18	59.5	60.1	39.2	39.7
11	0	0	1800	18	60.5	60.1	40.2	39.7
12	0	0	1800	18	59.8	60.1	39.6	39.7
13	0	0	1800	18	60.7	60.1	39.7	39.7

Based on the data from **Table 7**, the following regression equations were obtained:

$$\alpha Si_{(alloy)}=-287.596+0{,}334\cdot T+1.35\cdot SC-8.09\cdot 10^{-5}\cdot T^2+0.015\cdot SC^2-6.44\cdot 10^{-4}\cdot T\cdot SC; \quad (6)$$

$$CSi_{(alloy)}=-393.27+0.453T+1.65SC-1.16\cdot 10^{-4}\cdot T^2-4.49\cdot 10^{-3}\cdot SC^2-1.03\cdot 10^{-3}\cdot T\cdot SC. \quad (7)$$

Using these equations, 3D and planar visualizations of the effect of temperature and steel chips (SC) on the process parameters were generated using the MathCAD software [26] (**Fig. 7**).

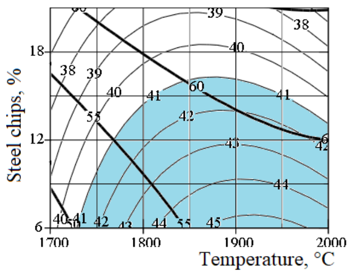


I – 3D Model, II – Horizontal Section

Fig. 7 Effect of Temperature and Steel Chips on Silicon Extraction (A) and Silicon Concentration (B) in the Alloy

Fig. 7 shows that 70-72.8% silicon extraction degree occurs in the 1760-2000°C temperature range with 27-30% SC.

Fig. 8 presents a combined view of the effect of temperature and SC quantity on process parameters. It shows that in the temperature range of 1728-2000°C, with 6-16.3% SC, a ferroalloy corresponds to ferrosilicon of the FeSi45 grade, with a silicon extraction degree of 50.2-61%.



(———) – αSi(alloy), %, (———) – CSi(alloy), %

Fig.8 Combined Information on the Effect of Temperature and Steel Chips on αSi(alloy) and CSi(alloy)

The experimental determination of optimal process parameters for producing ferroalloy from the mixture of SO and LC was conducted via electric smelting using the second-order rotatable designs method. Initially, the experiments were carried out with a charge that did not contain magnetite concentrate. The effect of SC and coke quantity on αSi(alloy) and CSi(alloy) was studied within the variable ranges shown in **Table 8**. At the same time, the experimental design matrix and results are presented in **Table 9**.

Table 8 Factor Levels and Variation Ranges for Studying the Effect of Coke and Steel Chips on the Smelting of Shalkiya Ore and Leaching Cakes of Vanadium-Containing Quartzites

Variables	Coded designation	Natural form	
		SC, %	**C, %*
Basic level	0	18	22
Variation range	Δ	3.5	3.5
Upper level	+1	26.5	24.8
Lower level	-1	9.5	19.2
Upper star-point	+1.414	30	26
Lower star-point	-1.414	6	18

*) C – Coke quantity

Table 9 Experimental Design Matrix and Results

№	Variables				Process parameters			
	Coded kind		*Natural kind*		*αSi(alloy) studied, %*	*αSi(alloy) calculated, %*	*CSi(alloy), studied, %*	*CSi(alloy), calculated, %*
	X1	*X2*	*SC, %*	*C, %*				
1	-1	-1	9.5	19.2	65.0	65.4	46.3	46.8
2	+1	-1	26.5	19.2	76.5	76.6	36.5	34.7
3	-1	+1	9.5	24.8	65.0	65.7	48.1	48.4
4	+1	+1	26.5	24.8	78.3	78.6	35.8	33.9
5	1.414	0	30	22	81.2	81.1	28.7	31.0
6	1.414	0	6	22	64.7	64.1	50.6	49.8
7	0	1.414	18	26	72.0	71.4	41.0	41.8
8	0	-1.414	18	18	70.0	69.8	40.6	41.2
9	0	0	18	22	71.3	72.1	41.2	42.0
10	0	0	18	22	71.8	72.1	41.0	42.0
11	0	0	18	22	72.0	72.1	42.0	42.0
12	0	0	18	22	72.2	72.1	43.0	42.0
13	0	0	18	22	73.0	72.1	42.9	42.0

Based on the data from **Table 9**, the following regression equations were obtained:

$$\alpha Si_{(alloy)}=18.95+0.167\cdot SC+3.91\cdot C+3.46\cdot 10^{-3}\cdot SC^2-9.18\cdot 10^{-2}\cdot C^2+1.89\cdot 10^{-2}\cdot SC\cdot C \quad (8)$$

$$CSi_{(alloy)}=31.25-0.139\cdot SC+1.655\cdot C-1.137\cdot 10^{-2}\cdot SC^2-3.16\cdot 10^{-2}\cdot SC^2-1.05\cdot 10^{-2}\cdot SC\cdot C \quad (9)$$

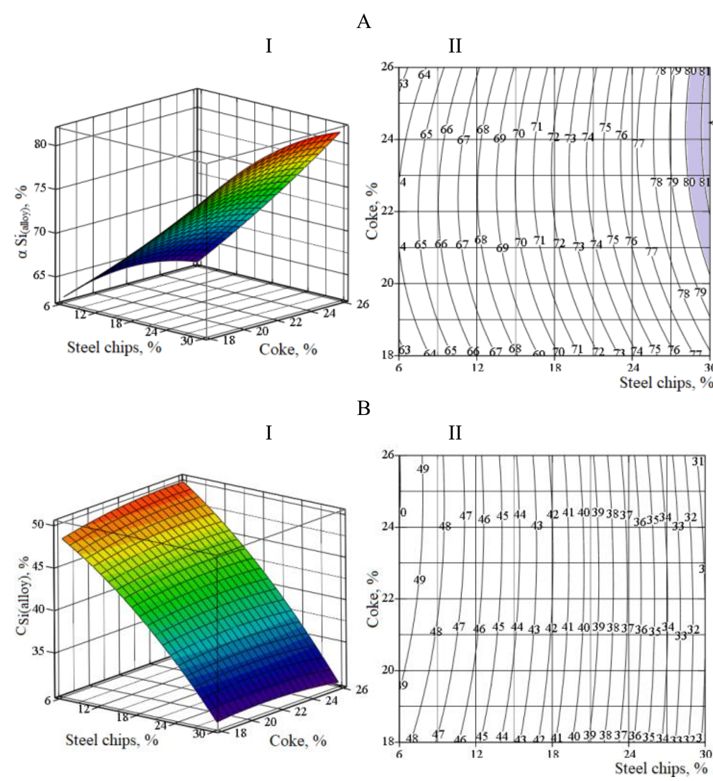
For the accepted confidence level of optimization parameters (≥95%), the Fisher criterion table value is 6.59 [33]. The calculated Fisher criterion values for Equations 8 and 9 are 1.37 and 5.44, respectively. Since the calculated Fisher values are lower than the table value, Equations 8 and 9 are considered adequate.

3D models and horizontal response surfaces were generated using these regression equations to illustrate the effect of steel chips and coke content on the process parameters.

Fig. 9 shows that the degree of silicon extraction into the alloy ranged from 62.6% to 81.6%. A high extraction degree (80-81.6%) was observed at 28.5-30% SC and 20.2-26% coke. The silicon concentration in the alloy ranged from 30.3% to 50.0%.

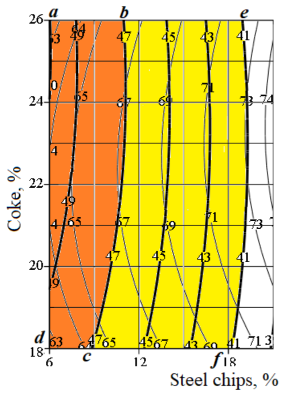
To determine the optimal parameters for SO and LC electric smelting, geometric optimization was performed by overlaying graphical images of response surface cross-sections (**Fig. 10**). The resulting visualization indicates that during electric smelting, ferrosilicon of two grades, FeSi45 and FeSi50, was formed (**Table 10**).

Fig. 10 and **Table 10** show that in the absence of magnetite concentrate, ferrosilicon of the FeSi45 grade is formed at 8.8-19.3% SC and 18.0-26.0% coke. The silicon extraction degree for ferrosilicon of the FeSi45 grade was 64.2-73.1%. Ferrosilicon of the FeSi50 grade, with the silicon extraction degree of 62.5-67.3%, is formed at 6.0-11% SC and 18-26% coke.



I – 3D Model, II – Horizontal Section

Fig. 9 Effect of Steel Chips and Coke on Silicon Extraction (A) and Silicon Concentration (B) in the Alloy



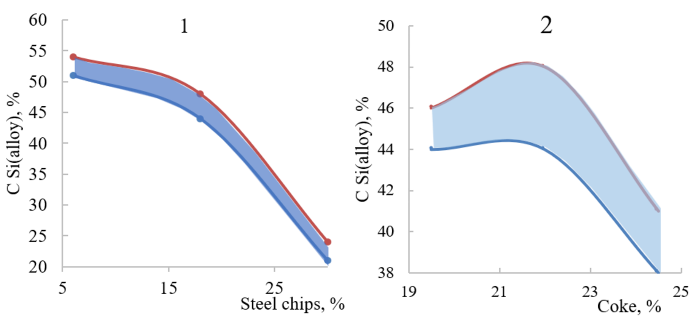
(———) – αSi(alloy), %, (**▬▬▬**) – Csi(alloy), %

Fig.10 Combined Graphical Information on the Effect of Steel Chips and Coke on αSi(alloy) and CSi(alloy)

Table 10 Process parameters of the areas in Fig. 10 corresponding to the obtained alloy grades

Area	Steel chips, %	Coke,%	αSi(alloy), %,	Csi(alloy), %	Alloy grade
abcd	6.0-11	18.0-26.0	62.5-67.3	47.0-50.0	FeSi50
befc	8.8-19.3	18.0-26.0	64.2-73.1	41.0-47.0	FeSi45

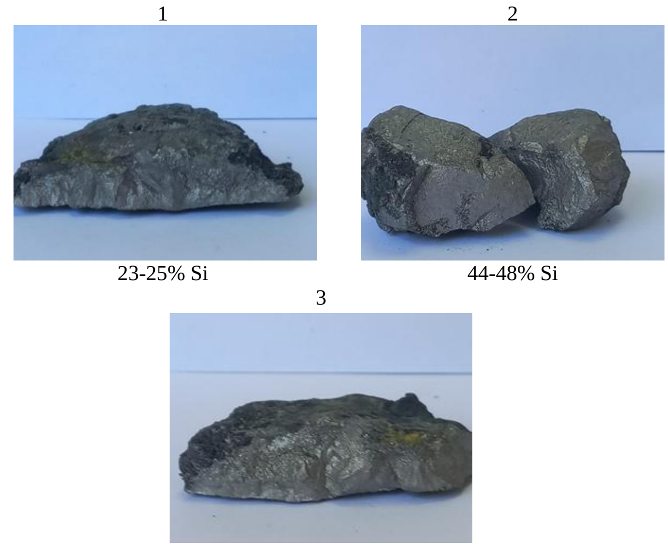
In the second stage of electric smelting, experiments were conducted in the presence of magnetite concentrate, 12% of the total mass of ore and cake. **Fig. 11** presents the research results. (The shaded area marks the silicon concentration boundaries.)



Quantities: 1-22% Steel Chips, 2-18% Coke

Fig. 11 Effect of Coke and Steel Chips on Silicon Concentration in the Alloy During Ore and Cake Smelting in the Presence of Magnetite Concentrate

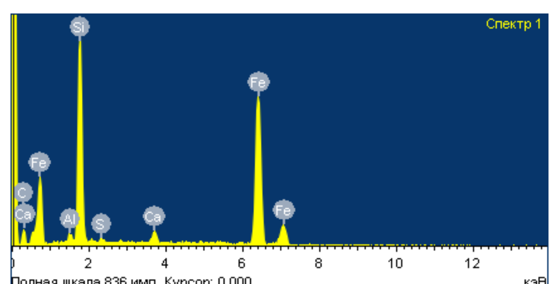
It is evident that at a constant coke quantity, an increase in SC reduces the silicon concentration in the alloy. The dependence CSi(alloy) = f(coke) at a continuous SC quantity exhibits an extremal character – increasing coke content beyond 22% leads to a decrease in CSi(alloy) due to the enhanced formation of gaseous SiO. Photographs of the smelted alloys are shown in **Fig. 12**.



Quantity of Raw Material as a Percentage of SO and LC Mass:
1) steel chips – 30%, coke – 22%; 2) steel chips – 18%, coke – 22%;
3) steel chips – 6%, coke – 22%

Fig. 12 Photographs of Alloys Obtained from the Ore and Cake Mixture in the Presence of Magnetite Concentrate

It is evident that, depending on the quantity of SC, different grades of ferrosilicon are formed: FeSi25 at 30% SC, FeSi45 at 18% SC, and FeSi50 at 6% SC. A SEM analysis of the alloy containing 45.7% Si, smelted from the second charge, is shown in **Fig. 13**.



Elements	Si	Al	S	Ca	Fe	C
Wt.%	45.7	1.7	0.6	1.6	48.0	2.4

Fig. 13 SEM Analysis of the Alloy

It should be noted that when smelting the ore and cake mixture in the presence of magnetite concentrate (MC), the silicon extraction degree into ferrosilicon of the FeSi45 grade increases from 72.4% to 80% as steel chips content rises from 6% to 30%. For ferrosilicon of the FeSi50 grade, the silicon extraction degree increases from 69.3% to 74.5%. These values are significantly lower in the absence of MC (64-73% for FeSi45 and 62-67% for FeSi50).

A comparison of the silicon extraction into ferrosilicon of the FeSi45 grade, obtained from thermodynamic modeling and electric smelting (**Figs. 7**, **8**, and smelting in the presence of magnetite), shows that the silicon extraction degree in electric smelting is 19-22% higher. This discrepancy is because thermodynamic modeling does not account for a solid charge bed in the electric furnace, which retains gaseous SiO. Therefore, silicon extraction into ferrosilicon is significantly higher when smelting with a charge bed.

Fig. 14 shows the sublimates deposited on the electrode holder and their SEM analysis. They contain 25.2% zinc and 13.7% lead, respectively, which were extracted from the sublimates at 98.6% and 98.2%.
The obtained results on the combined electric-thermal processing of sulfide ore and leaching cakes of vanadium-containing quartzites can also be applied to the processing of other sulfide zinc-containing ores with a high SiO_2 content, such as the primary sulfide ore of the Zhairem deposit, which contains 3.5% Zn, 0.85% Pb, and 50% SiO_2 [34-36].

Elements	*Zn*	*Pb*	*Si*	*S*	*Mg*
Wt.%	25.2	13.7	22.3	1.9	2.1
Elements	*Ca*	*K*	*Fe*	*C*	*O*
Wt.%	1.8	1.7	1.63	3.0	29.6

Fig. 14 Photograph and SEM Analysis of Sublimates

CONCLUSION

Based on the theoretical and experimental studies on the possibility of producing ferrosilicon and zinc- and lead-containing sublimates from the mixture of sulfide zinc ore and leaching cake of vanadium-containing quartzites, the following conclusions were drawn:
1. Under equilibrium conditions:
- In the ore–cake – magnetite concentrate – coke – steel chips system, increasing the coke quantity from 20% to 25% raises the silicon extraction degree into the alloy from 62.95% to 70.98%.
- Increasing the steel chips quantity from 6% to 30% enhances the silicon extraction degree into the alloy from 50.17% to 73.76% at 1800°C, while simultaneously reducing the silicon concentration in the alloy from 48.13% to 33.93%.

Ferrosilicon of the FeSi45 grade is formed at 1728-2000°C with 6-16.3% steel chips.
2. The optimal parameters for producing ferrosilicon of the FeSi45 grade in an arc furnace, with the silicon extraction degree of 64.2-73.1%, from the mixture of the Shalkiya ore and leaching cake, are 8.8-19.3% steel chips and 18.0-26.0% coke. Ferrosilicon of the FeSi50 grade, with the silicon extraction degree of 62.5-67.3%, is formed at 6.0-11% steel chips and 18-26% coke.
3. Electric smelting of the ore–leaching cake mixture in the presence of 12% magnetite concentrate and 22% coke produces ferrosilicon of different grades: FeSi25 containing 23-25% Si (at 30% steel chips), FeSi45 containing 44-48% Si (at 18% steel chips), and FeSi50 containing 52-54% Si (at 6% steel chips). For FeSi45 production, the silicon extraction degree was 72.4-80.6%, and for FeSi50, it was 69.3-74.5%.
4. The sublimates formed during electric smelting of the ore–leaching cake mixture contain 25.2% zinc and 13.7% lead. The extraction of zinc and lead into the sublimates was 98.6% and 98.2%, respectively.
5. The results obtained on ferrosilicon smelting using leaching cakes of vanadium-containing quartzites can be applied to processing other sulfide zinc-bearing silicon-containing ores, such as those from the Zhairem deposit.

Acknowledgements: This research is funded by the Industrial Development Committee of the Ministry of Industry and Infrastructure Development of the Republic of Kazakhstan (Grant №. BR19777171).

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