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The effect of iron on the production of ferrosilicon and the volatilization of non-ferrous metals from a mixture of sulfide ores from the Shalkiya and Zhayrem deposits

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Abstract. The article presents the results of studies on the complex processing of ores from the Shalkiya and Zhayrem deposits, a distinctive feature of which is not only a low degree of floatability (due to close mutual intergrowth of zinc and lead ore minerals with non-metallic minerals), but also a high content (40-50%) of silica. The studies were carried out by thermodynamic modeling methods using the HSC-6.0 software package based on the principle of minimum Gibbs energy, second-order planning and electric smelting in an arc single-electrode furnace of sulfide ores from the Shalkiya and Zhayrem deposits (with a ratio of 1:1) together with carbon (coke) and iron (steel cuttings). The effect of temperature and the amount of iron on the equilibrium distribution of silicon, zinc, lead, the composition of the silicon-containing alloy and sublimates containing zinc and lead was determined. Conditions for the equilibrium formation of grade ferrosilicon with the transition of 60 to 85% silicon, at least 99% zinc and 48-89% lead into sublimates were determined. Ferrosilicon grade FeSi45 was obtained by electric smelting of a mixture of the Shalkiya and Zhayrem ores in the presence of 26% coke and 18% steel cuttings, and ferrosilicon grade FeSi25 was obtained in the presence of 26% coke and 38% iron. Sublimates of electric smelting contain 25.0-26.1% zinc and 10.5-11.8% lead.

Keywords: *lead-zinc polymetallic ores, ferrosilicon, sublimates, thermodynamic modelling, electrosmelting.*

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1. Introduction

The existing approaches to zinc production and extraction, mainly based on traditional pyrometallurgical and hydrometallurgical processing of sulfide ores, face a number of significant difficulties [1-3]. Despite the fact that up to 80% of the world's zinc is obtained from sulfide raw materials according to the classical scheme [4-9], it is characterized by a significant number of stages: crushing, grinding, enrichment, roasting, leaching, solution purification, electrolysis and obtaining cathode zinc. This approach leads to relatively low rates of valuable metal extraction and the formation of a large amount of waste, such as enrichment tailings and leaching cakes. Research in the field of enrichment and hydrometallurgical processing of lead-zinc ores is also not able to completely solve the problem of low zinc and lead extraction into concentrate, and is also associated with the formation of multi-ton waste – enrichment tailings [10-13]. These problems are especially relevant for the Shalkiya and Zhayrem complex polymetallic ore deposits. The reserves of these deposits are significant: Shalkiya contains 129.35 million tons of balance and 119.56 million tons of off-balance ores (3.49-4.27% Zn, 0.8-1.28% Pb) [14-16], and Zhayrem contains 136.7 million tons of barite-polymetallic ore and 62.9 million tons of lead-zinc barite-free ore [17], containing 3.4-5.73% Zn, 0.56-1.5% Pb [18]. A distinctive feature of these ores is the high silica content (49.63-56.0%), which makes them not only a source of non-ferrous metals, but also a potential raw material for the production of silicon-containing ferroalloys, such as ferrosilicon.

In M. Auezov South Kazakhstan University, together with National Center for Complex Processing of Mineral Raw Materials of the Republic of Kazakhstan, a technology for complex processing of complex polymetallic ores of the Shalkiya and Zhayrem deposits is being developed [19-21]. The technology is based on the joint production in one unit – an electric furnace, of several types of products - silicon ferroalloy and non-ferrous metal sublimates. The developed technology significantly increases the efficiency of non-ferrous metal extraction and the complex use of raw materials, significantly reducing. Previously, studies were focused on the processing of ore from the Shalkiya deposit. At the present stage, joint processing of the Shalkiya and Zhayrem ores is becoming relevant, with the organization of their industrial processing in one of the regions of Kazakhstan. Previously, studies were conducted to determine the thermodynamic probability of joint processing of a mixture of the Shalkiya and Zhayrem ores with a carbon and iron content of 22% [22].

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The paper presents the results of studies on the effect of the amount of iron on the formation of ferroalloy and distillation of non-ferrous metals in relation to the joint processing of ores from the Zhayrem and Shalkiya deposits, with a ratio of 1:1.

2. Materials and methods

The studies were carried out by thermodynamic modeling using the HSC Chemistry 6.0 software package, with the Equilibrium Compositions module [23]. To calculate the equilibrium distribution of components (α, %), an algorithm created by employees of Department of Metallurgy of M. Auezov SKU was used [24].

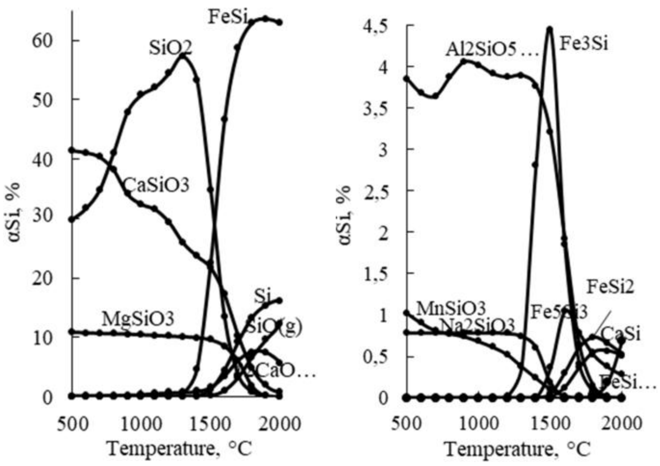
Calculations were carried out in the temperature range of 500-2000°C with an interval of 100°C and a pressure of 1 bar. The amount of carbon was determined based on what was theoretically necessary for the complete reduction of zinc, lead, silicon and iron, and amounted to 26% of the mass of the ore mixture. The amount of iron in the mixture varied from 13 to 47% of the mass of the ore mixture. Composition of the original mixture, mass. %: 49.1 SiO_2, 19.1 CaO, 7.9 Al_2O_3, 3.1 FeS_2, 1.3 PbS, 6.2 ZnS, 3.6 MgO, 0.8 MnO, 5.7 Fe_2O_3, 0.4 Na2O, 3.1 $BaSO_4$.

The determination of the optimal technological parameters for ore processing was carried out using the method of second-order rototable planning (Box-Hunter plan) [25, 26]. The MathCAD program [27] was used to visualize the optimization parameters and create three-dimensional and flat graphic models.

3. Results and discussion

Using the software package, primary information was obtained on the quantitative (kg) distribution of substances in the system of 50 kg Shalkiya ore, 50 kg Zhayrem ore, 26 kg carbon, 30 kg iron, using the algorithm [24] the equilibrium degree of distribution of components in the system was calculated.

From Figure 1 it is evident that the formation of FeSi and Fe_3Si begins at a temperature of 1200ºC, Fe_5Si_3 at 1400ºC, $FeSi_2$ and $FeSi_{2,33}$ at 1500ºC, CaSi at 1800ºC. The highest degree of distribution of silicon in elemental form is observed at 2000ºC and is 16.1%.

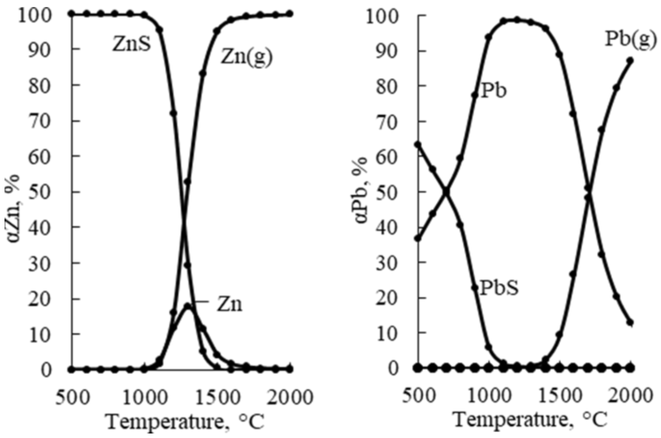


(a) (b)

Figure 1. Effect of temperature on the equilibrium distribution of silicon: (a) – formation of ferrosilicon phases and elemental silicon; (b) – transition of silicon into the gas phase in the form of SiO

A further increase in temperature leads to a decrease in the proportion of silicon in elemental form, which is associated with the transition of silicon into gaseous oxide – SiOg (at 2000ºC, the degree of extraction of silicon in SiOg is 12.3%).

Figure 2 shows the effect of temperature on the equilibrium distribution of zinc and lead, from which it is evident that zinc simultaneously begins to be reduced and converted into gas at 1100ºC. At 1700ºC, more than 99% of it passes into the gas phase.

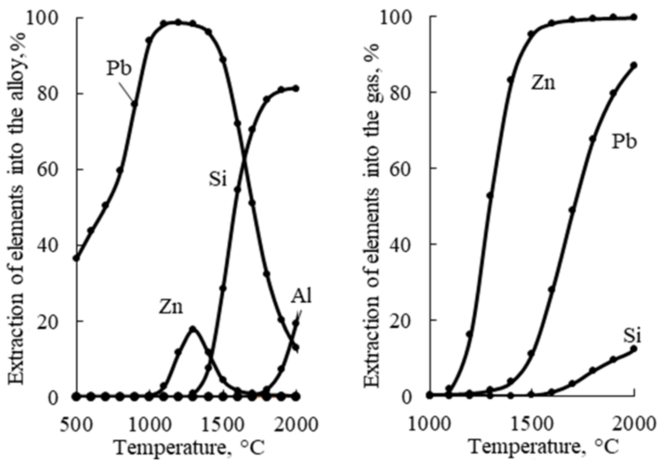


(a) (b)

Figure 2. Effect of temperature on the equilibrium degree of distribution of zinc (a) and lead (b)

Lead in the system is almost completely reduced at 1200-1300ºC. Then, with increasing temperature, it passes into gas, reaching a maximum of 87.03% at a temperature of 2000ºC.

Depending on the temperature, the following elements pass into the alloy: Al, Ca, Fe, Mg, Mn, Na, Pb, Si, Zn, and the following elements pass into the gas phase: Al, Ca, Mg, Mn, Na, Pb, Si, Zn. Figure 3 shows the extraction of elements into the alloy and into the gas phase.

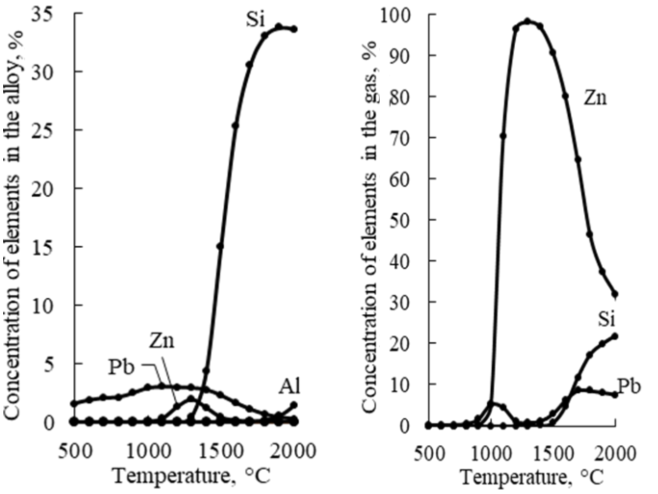


(a) (b)

Figure 3. Effect of temperature on the degree of extraction of elements into the alloy (a) and into the gas phase (b)

The highest degree of silicon extraction into the alloy is observed at 2000ºC (81.2%). Aluminum is transferred to the alloy to the maximum (19.3%) at 2000ºC. The degree of silicon extraction (ΣαSi(g) = αSi(g) + αSiO(g)) into the gas phase is 3.26% at 1700ºC and 12.3 at 2000ºC.

Figure 4 shows information on the content of Si, Pb, Zn, Al in the alloy (excluding iron) and the concentration of Zn, Si, Pb in the gas phase (excluding Ca, Mg, Mn, Na, CO, CO_2, SO_2).

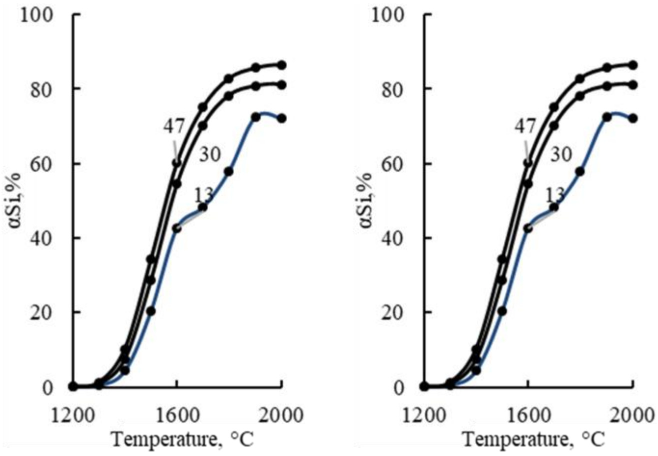


(a) (b)

Figure 4. Effect of temperature on the content of elements in the alloy (a) and gas phase (b)

At 1800ºC the alloy contains 65.18% Fe, 33.06% Si, 0.16% Al, 0.02% Ca, 0.03% Mg, 0.84% Mn, 0.01% Na, 0.67% Pb, 0.04% Zn. The maximum silicon content in the alloy (33.75%) is observed at 1900ºC. The aluminum content in the alloy reaches 1.5% at 2000ºC. The content of elements in the gas phase (excluding CO(g), CO_2(g), COS(g), CS2(g), CS(g), SO2(g)) at 1800ºC is as follows: 46.46% Zn, 8.55% Pb, 17.25% Si, 0.02% Al, 0.05% Ca, 12.75% Mg, 1.78% Mn, 3.3% Na, 9.83% O, 0.01% S. The highest concentration of zinc in the gas phase (98.1%) is observed at 1300ºC, and lead – 8.6% at 1700ºC. Silicon (as the sum of Si(g) and SiO(g)) also passes into the gas phase, its content is maximum at 2000ºC – 21.7%.

Effect of temperature and iron content on the degree of silicon extraction and its concentration in the alloy is shown in Figure 5. As follows from Figure 5, changing the amount of iron significantly affects the technological parameters.



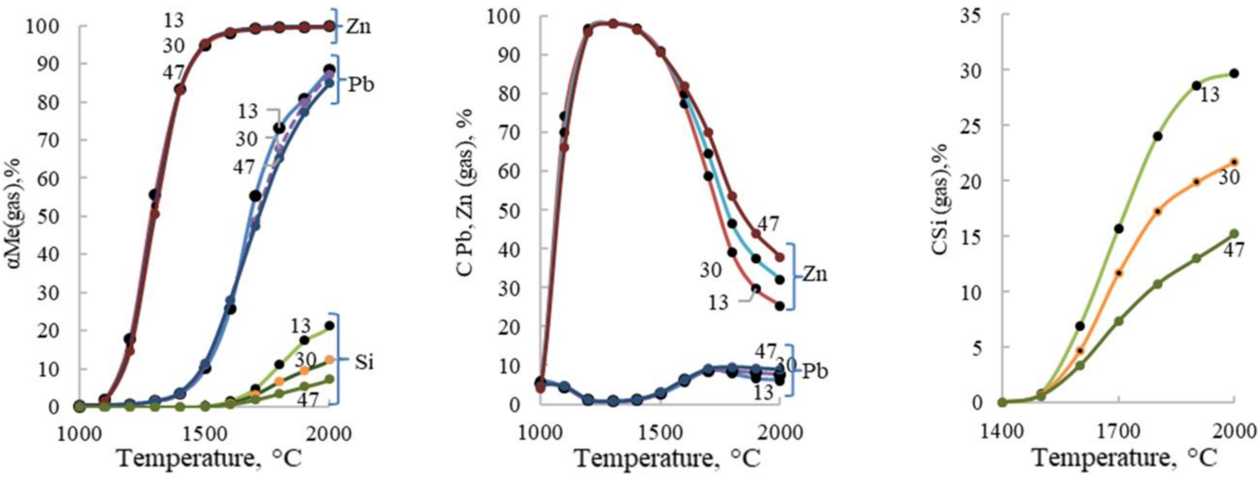
(a) (b)

Figure 5. Effect of temperature and iron on the extraction (a) and concentration (b) of silicon in the alloy. The numbers near the lines are the amount of iron, %

With an increase in the amount of iron in the system, the degree of silicon extraction into the alloy increases, while the concentration, on the contrary, decreases. The maximum degree of silicon extraction (86.5%) is observed at 2000ºC and 47% iron. The highest concentration of silicon in the alloy (45.9%) is observed at 1900ºC and a minimum iron content (13%), while the degree of silicon extraction does not exceed 72.4%.

Changing the amount of iron does not significantly affect the degree of zinc and lead extraction into the gas (Figure 6a). The degree of silicon extraction into the gas phase in the form of Σ (SiO and Si) decreases with increasing iron. For example, at a temperature of 2000ºC and 13% iron, the degree of silicon extraction into the gas is 21.2%, and at 47% iron – 7.3%.

From Figure 6b it is evident that changing the amount of iron has little effect on the lead concentration in the gas. The maximum lead concentration is observed at 1800ºC (7.7-9.5%). Up to 1600ºC, the amount of iron has virtually no effect on the zinc concentration in the gas. Then, up to 2000ºC, with an increase in the amount of iron, the zinc concentration increases. The maximum zinc concentration (98.2%) occurs at 1300ºC regardless of the amount of iron.



(a) (b) (c)

Figure 6. Effect of temperature and amount of iron on the degree of metal extraction into gas (a), concentration of zinc and lead (b) and silicon (c) in the gas phase. The numbers near the lines are the amount of iron, %

The silicon content in the gas phase (Figure 6c) decreases significantly with increasing iron content. At 1800ºC and 13% iron, the silicon concentration in the gas is 24.04%, and at 47% iron – 10.73%. In order to determine the optimal equilibrium parameters of the effect of iron on the formation of alloy and lead-zinc sublimates from the mixture of the Zhayrem and Shalkiya ores, the studies were conducted using the second-order rototable planning method. The study planning matrix is given in Table 1.

Table 1. Planning matrix and results of studies of the effect of temperature and amount of iron on technological indicators

No.	Variables				$\alpha Si_{(alloy)}$, %	$CSi_{(alloy)}$, %	$\alpha Zn_{(gas)}$, %	$CZn_{(gas)}$, %	$\alpha Pb_{(gas)}$, %	$CPb_{(gas)}$, %	$\alpha Si_{(gas)}$, %	$CSi_{(gas)}$, %
	Coded view		Natural view									
	X_1	X_2	T, °C	Fe, %								
1	-1	-1	1743.6	17.9	67.00	38.50	99.42	50.00	58.60	7.90	7.50	20.00
2	+1	-1	1956.4	17.9	75.50	41.00	99.78	29.30	85.20	6.33	16.80	27.00
3	-1	+1	1743.6	42.1	78.30	27.00	99.34	61.50	56.40	9.20	3.00	10.00
4	+1	+1	1956.4	42.1	85.38	27.00	99.73	39.00	82.80	8.80	7.20	15.80
5	1.414	0	2000	30	81.18	33.56	99.80	32.01	87.10	7.50	12.30	21.76
6	-1.414	0	1700	30	70.22	30.57	99.17	64.57	48.82	8.60	3.26	11.69
7	0	1.414	1850	47	84.26	26.59	99.58	48.82	71.25	9.38	4.47	11.87
8	0	-1.414	1850	12	65.20	43.35	99.69	34.39	77.08	7.10	14.26	26.32
9	0	0	1850	30	79.54	33.40	99.63	41.96	73.72	8.33	8.15	18.57
10	0	0	1850	30	78.80	33.50	99.63	41.80	72.80	8.42	8.10	18.40
11	0	0	1850	30	80.40	33.30	99.65	42.20	73.83	8.30	8.22	18.60
12	0	0	1850	30	79.10	33.20	99.64	41.70	73.75	8.26	8.25	18.30
13	0	0	1850	30	80.00	33.80	99.62	42.30	73.85	8.38	8.13	18.70

Based on the results of the research according to the plans presented in Table 1, the regression equations were obtained:

$$\alpha Si_{(alloy)} = -515.189 + 0.569 \cdot T + 1.863 \cdot Fe - 1.415 \cdot 10^{-4} \cdot T^2 - -1.43 \cdot 10^{-2} \cdot Fe^2 - 2.757 \cdot 10^{-4} \cdot T \cdot Fe \quad (1)$$

$$CSi_{(alloy)} = -206.971 + 0.259 \cdot T + 0.091 \cdot Fe - 6.386 \cdot T^2 + +4.979 \cdot 10^{-3} \cdot Fe^2 - 4.855 \cdot 10^{-4} \cdot T \cdot Fe \quad (2)$$

$$\alpha Zn_{(gas)} = 74.723 + 0.025 \cdot T - 0.016 \cdot Fe - 6.369 \cdot 10^{-6} \cdot T^2 + 2.049 \cdot Fe^2 + 6.214 \cdot 10^{-6} \cdot T \cdot Fe \quad (3)$$

$$CZn_{(gas)} = 1154.65 - 1.124 \cdot T + 1.156 \cdot Fe + 2.78 \cdot 10^{-4} \cdot T^2 - 1.318 \cdot 10^{-3} \cdot Fe^2 - 3.495 \cdot 10^{-4} \cdot T \cdot Fe \quad (4)$$

$$\alpha Pb_{(gas)} = -1030.71 + 1.073 \cdot T - 0.147 \cdot Fe - 2.555 \cdot 10^{-4} \cdot T^2 + 1.427 \cdot 10^{-3} \cdot Fe^2 - 3.884 \cdot 10^{-5} \cdot T \cdot Fe \quad (5)$$

$$CPb_{(gas)} = -24.16 + 0.043 \cdot T - 0.318 \cdot Fe - 1.465 \cdot T^2 - 4.849 \cdot 10^{-4} \cdot Fe^2 + 2.268 \cdot 10^{-4} \cdot T \cdot Fe \quad (6)$$

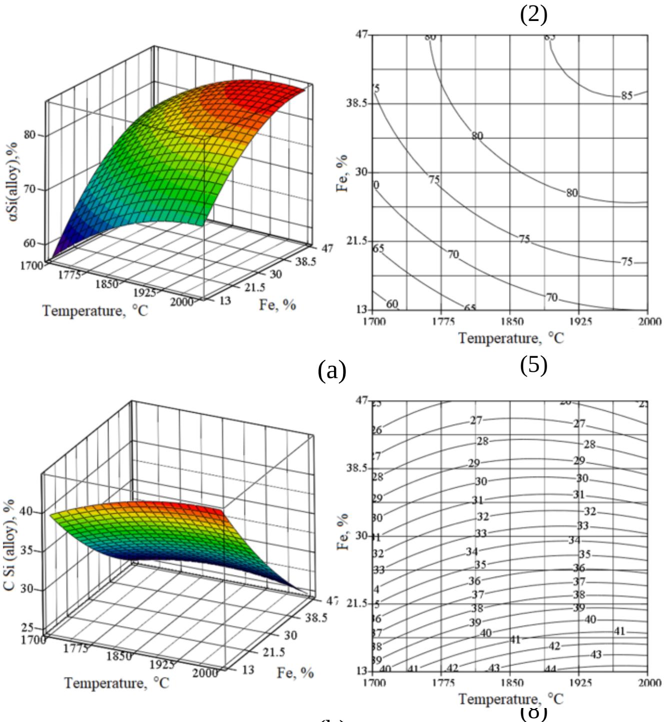
$$\alpha Si_{(gas)} = -146.464 + 0.12 \cdot T + 1.293 \cdot Fe - 1.606 \cdot 10^{-4} \cdot T^2 + 4.173 \cdot 10^{-3} \cdot Fe^2 - 9.903 \cdot 10^{-4} \cdot T \cdot Fe \quad (7)$$

$$CSi_{(gas)} = -286.557 + 0.307 \cdot T - 0.148 \cdot Fe - 7.261 \cdot 10^{-5} \cdot T^2 + 2.479 \cdot 10^{-3} \cdot Fe^2 - 2.33 \cdot 10^{-4} \cdot T \cdot Fe \quad (8)$$

Using which 3D models and their horizontal response surfaces were constructed (Figures 7-10).

From Figure 7 it follows that the highest degree of silicon extraction into the alloy – 85.69% is observed at a temperature of 1960ºC and 47% iron, and the maximum concentration is 44.5% at 1960ºC and 13% iron.

From Figures 8-10 it is evident that at 13% iron and a temperature of 2000ºC the maximum degree of zinc extraction is 99.82%, lead – 89.49% and silicon – 21.08% into the gas phase, as well as the highest silicon content in the gas phase – 30.27%. The highest concentration of zinc (71.8%) and lead (9.36%) in the gas phase is observed at 47% iron and a temperature of 1700ºC and 1775ºC, respectively.



(b)

Figure 7. 3D models and planar projections illustrating the effect of temperature and iron content on silicon behavior: (a) – degree of silicon extraction into the alloy; (b) – silicon concentration in the alloy

The basis for determining the optimal equilibrium technological parameters was the silicon concentration in the alloy corresponding to its grade.

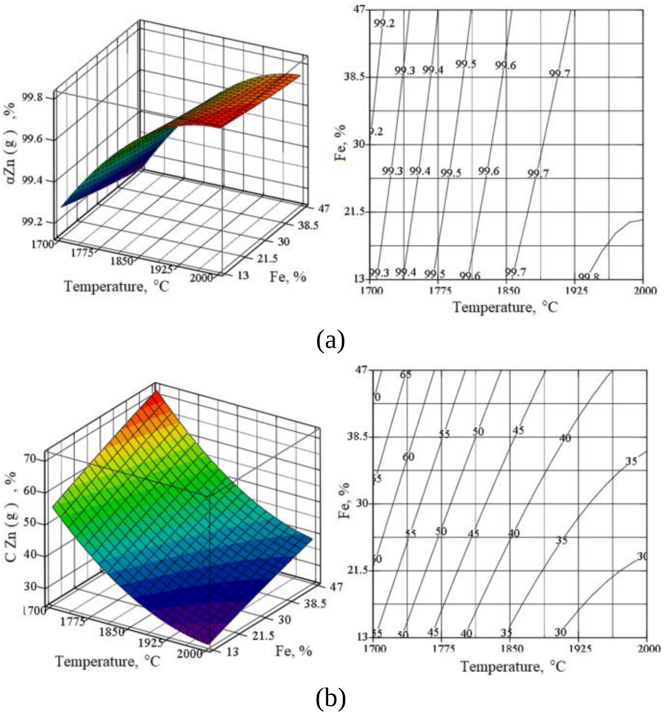


Figure 8. 3D models and planar projections illustrating the effect of temperature and iron content on zinc behavior: (a) – degree of zinc extraction into the alloy; (b) – zinc concentration in the gas phase

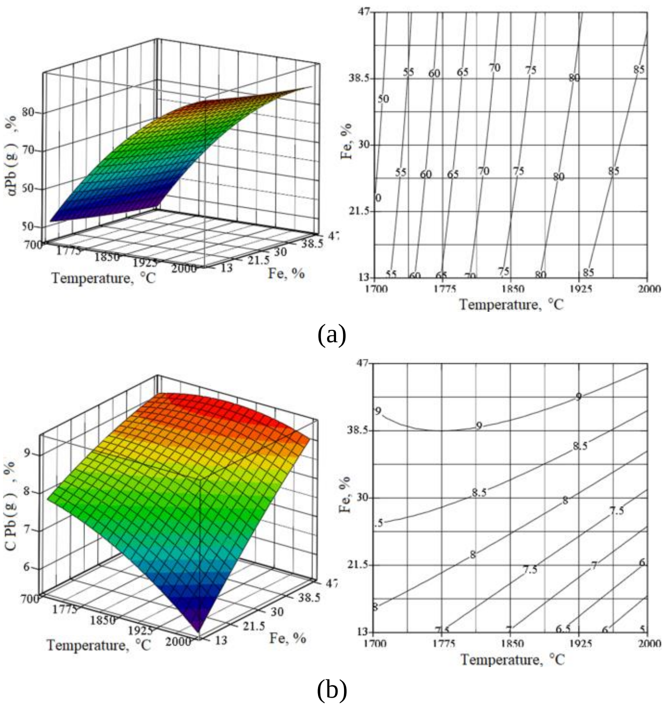


Figure 9. 3D models and planar projections illustrating the effect of temperature and iron content on lead behavior: (a) – degree of lead extraction into the alloy; (b) – lead concentration in the gas phase

Geometric optimization was performed by superimposing the dependencies αSi(alloy) = f(T, Fe) and CSi(alloy) = f(T, Fe) on one horizontal plane with the determination of αZn(gas), αPb(gas) and αSi(gas) at the points of the boundary regions (Figure 11 and Table 2). Table 2 shows the technological indicators at the points of Figure 11.

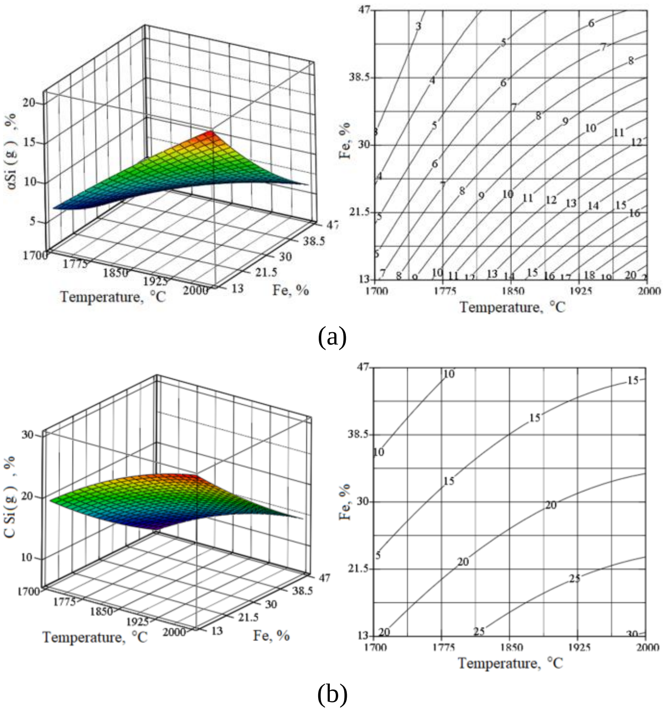


Figure 10. 3D models and planar projections illustrating the effect of temperature and iron content on silicon behavior in the gas phase: (a) – degree of silicon extraction; (b) – silicon concentration in the gas phase

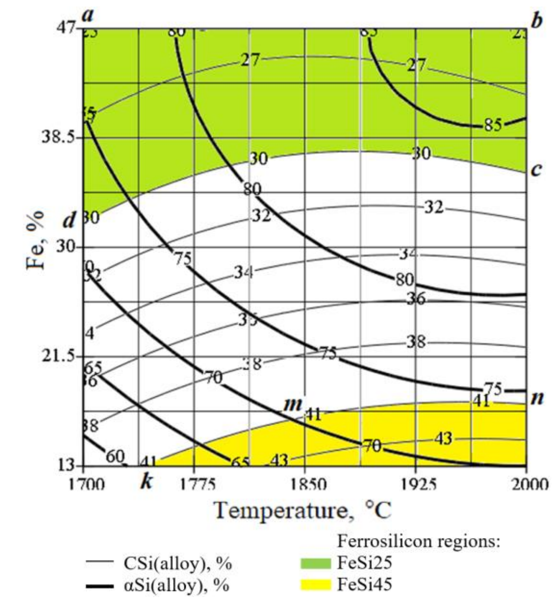


Figure 11. Combined picture of the effect of temperature and amount of iron on technological parameters

It is evident from Figure 11 that ferrosilicon grade FeSi25with the extraction degree of 75.9-85.5% silicon is formed in the temperature range of 1700-2000ºC and 35.87-47% iron. At the same time, 99.1-99.2% zinc, 47.2-86.0% lead, and 2.0-10.0% silicon pass into the gas phase containing 34.7-71.8% Zn, 8.0-9.1% Pb, and 6.1-11.4% Si.

In the temperature range of 1741-2000ºC at 13-17.83% iron, ferrosilicon grade FeSi45 is formed, into which silicon passes by 60.8-74.2%. The content of metals in the gas phase: zinc – 25.7-48.4%, lead – 5.4-7.7%, silicon – 21.8-30.3%. In this case, 99.4-99.8% Zn, 59.4-89.5% Pb, 21.8-30.3% Si pass into the gas phase.

Table 2. Values of technological parameters at the points of Figure 11

Points of Figure	T, °C	Fe, %	$\alpha Si_{(alloy)}$, %	$CSi_{(alloy)}$, %	$\alpha Zn_{(gas)}$, %	$CZn_{(gas)}$, %	$\alpha Pb_{(gas)}$ %	$CPb_{(gas)}$, %	$\alpha Si_{(gas)}$, %	$CSi_{(gas)}$, %	Alloy grade
a	1700	47	75.9	24.9	99.1	71.8	47.2	9.1	2.0	6.1	FeSi25
b	2000	47	85.5	24.7	99.8	38.6	84.8	9.1	6.2	14.5	
c	2000	35.87	84.0	29.9	99.8	34.7	86.0	8.0	10.0	19.0	
d	1700	31.9	71.9	30.0	99.2	64.9	48.7	8.7	2.9	11.4	
k	1741	13	60.8	41.0	99.4	48.4	59.4	7.7	8.9	21.8	FeSi45
m	1845	16.6	70.1	41.1	99.7	36.5	75.0	7.3	12.6	24.5	
n	2000	17.83	74.2	41.0	99.8	27.7	88.6	6.0	18.4	27.7	
l	2000	13	70.0	44.5	99.8	25.7	89.5	5.4	21.1	30.3	

Photographs of ferroalloys obtained by electric smelting of batches No. 1 and No. 2 are shown in Figure 12. SEM analysis of the alloy of batch No. 2 is shown in Figure 13.

(a) (b)

Figure 12. Photographs of the obtained ferroalloys. (a) – batch No. 1, (b) – batch No. 2

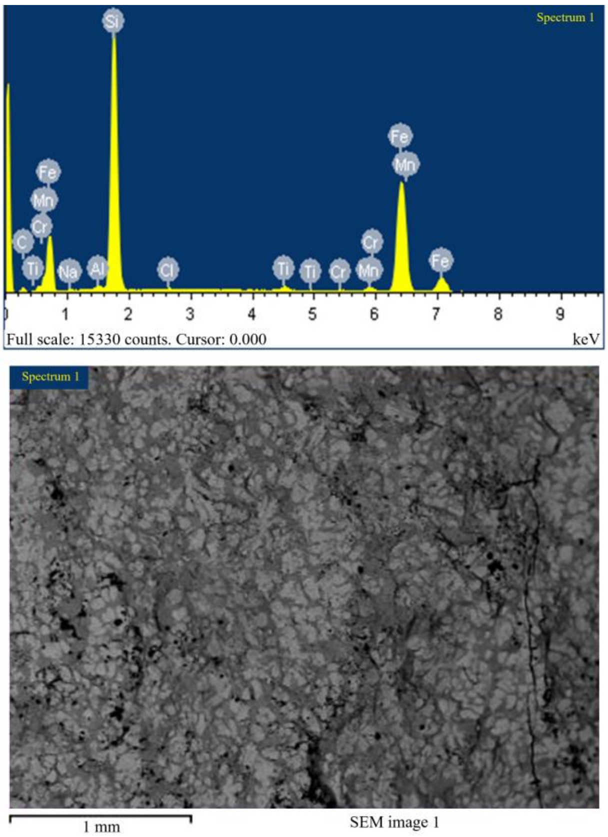


Figure 13. SEM microstructure and EDS spectrum of the alloy obtained from batch No. 2. Elemental composition (wt.%): 8.59 C, 0.46 Na, 0.40 Al, 33.45 Si, 0.26 Cl, 0.91 Ti, 0.30 Cr, 1.47 Mn, and 54.17 Fe.

Experimental exploratory electric smelting of the mixture of the Shalkiya and Zhayrem ores with different amounts of iron was carried out. (A detailed description of the electric smelting technique is presented in [28, 29]). The electric smelting of batch (No. 1) containing the mixture of the Shalkiya and Zhayrem ores, 26% coke, and 16.4% iron yielded ferrosilicon with a silicon content of 36.0-41.5%, which corresponds to ferrosilicon grade FeSi45 [30].

The resulting sublimates contain 27.0-29.1% zinc and 12.5-14.2% lead. The electric smelting of batch (No. 2) containing the mixture of the Shalkiya and Zhayrem ores, 26% coke, and 38% iron yielded ferrosilicon with a silicon content of 28.8-37.2%, which corresponds to ferrosilicon grade FeSi25. The process resulted in the formation of sublimates containing 25.0-26.1% zinc and 10.5-11.8% lead (the analysis of the sublimates was carried out by titrimetric method in Central Analytical Laboratory of A-Mega Trading LLP).

4. Conclusions

Based on the obtained results on the effect of the amount of iron on the formation of ferroalloy and distillation of non-ferrous metals during the processing of the mixture of ores from the Zhayrem and Shalkiya deposits, in a ratio of 1:1, it was established that:

Under equilibrium conditions:

- the interaction products in the system are: $CO_{(g)}$, FeSi, $CaSiO_3$, $FeSiO_3$, $*2CaO*SiO_2$, $SiO_{(g)}$, CaS, $MgSiO_3$, $CaO*Al_2O_3$, Fe_3Si, ZnS, $Ca_{(g)}$, Al_2O_3, Al_2SiO_5(A), $Zn_{(g)}$, FeO, Si, $*3CaO*Al_2O_3$, $Mg_{(g)}$, BaO, Al, MgO, CaO, $Al_{(g)}$, Pb, $MnSiO_3$, $Pb_{(g)}$, Fe_5Si_3, PbS, Na_2SiO_3, Zn, CaSi, Mn, $Mn_{(g)}$, MnO, $FeSi_2$, $CO_{2(g)}$, $Na_{(g)}$, $FeSi_{2.33}$, $*2CaO*Al_2O_3$, $COS_{(g)}$, $Si_{(g)}$, $FeSi_{2.43}$.

– with an increase in the amount of iron in the system, the degree of silicon extraction into the alloy increases, while the concentration, on the contrary, decreases;

– ferrosilicon grade FeSi25, which contains 24.7-30% Si, is formed in the range of 1700-2000ºC in the presence of 35.87-47% iron. The degree of silicon extraction into the alloy is 75.9-85.5%. 34.7-71.8% zinc, 8.0-9.1 lead and 6.1-11.4% silicon pass into sublimates;

– ferrosilicon grade FeSi45 is formed in the range of 1741-2000ºC with the iron content of 13-17.83%. The degree of silicon extraction into the alloy is 60.8-74.2%. The sublimes contain 25.7-48.4% zinc, 5.4-77% lead and 21.8-30.3% silicon.

Ferrosilicon grade FeSi45 was obtained by electric smelting of the mixture of the Shalkiya and Zhayrem ores in the presence of 26% coke and 18% steel cuttings, and ferrosilicon grade FeSi25 was obtained in the presence of 26% coke and 38% iron. The sublimes formed in this case contain 25.0-26.1% zinc and 10.5-11.8% lead.

Author contributions

Conceptualization: DKA, VMS; Data curation: DKA, VMS; Formal analysis: VMS; Funding acquisition: DKA; Investigation: VMS, ADB, TIA; Methodology: VMS; Project administration: ADB; Resources: DKA, VMS; Software: VMS; Supervision: DKA, VMS; Validation: ADB, TIA; Visualization: ADB, TIA; Writing – original draft: VMS, ADB, TIA; Writing – review & editing: DKA. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Шалхия және Жәйрем сульфидті кендерінің қоспасынан түсті металдарды айдау және кремнийлі ферроқорытпаны алуда темірдің әсері

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[1]Қазақстан Республикасының минералдық шикізатты кешенді өңдеу жөніндегі ұлттық орталығы, Алматы, Қазақстан
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Аңдатпа. Мақалада Шалқия және Жәйрем кен орындарының кендерін кешенді өңдеу бойынша зерттеулердің нәтижелері келтірілген, ондағы флотациялаудың төмен дәрежесінде ғана емес (мырыш пен қорғасын кенінің минералдарының металл емес минералдармен өзара тығыз өсуіне байланысты), сонымен қатар кремнеземнің жоғары мөлшерілігімен (40-50%) айрықша ерекшеленеді.Зерттеулер Шалқия және Жәйрем кен орындарындағы сульфидті кендерді (1:1 қатынасымен) көміртегімен (кокспен) және темірмен (темір жоңқасымен) бір электродты доғалы пеште электрлі балқытумен, екінші ретті жоспарлаумен және Гиббс энергиясының минималды принципіне негізделген HSC-6.0 бағдарламалық кешенін қолдану арқылы термодинамикалық модельдеу әдістерімен жүргізілді. Температура мен темір мөлшерінің кремнийқұрамдас қорытпаның, мырыш пен қорғасыны бар айдаулардың құрамын және кремнийдің, мырыштың, қорғасынның біртекті таралуына әсері анықталды. Құрамында 60-тан 85% кремнийге, кемінде 99% мырыш және 48-89% қорғасын айдауларына өтетін сортты ферросилиций түзілудің тепе-теңдік шарттары анықталды. Шалқия және Жәйрем кендерін электрлібалқытуда қоспа құрамы 26% кокс және 18% болат жоңқасының қатысуымен FeSi45 маркалы ферросилиций, ал 26% кокс және 38% темір жоңқасының қатысуында FeSi25 ферросилиций алынды. Электрлібалқыту айдаулары 25.0-26.1% мырыш пен 10.5-11.8% қорғасыннан тұрады.

Негізгі сөздер: *мырыш пен қорғасын полиметалл кендері, ферросилиций, айдаулар, термодинамикалық модельдеу, электробалқыту.*

Влияние железа на получение кремнистого ферросплава и отгонку цветных металлов из смеси сульфидных руд Шалкия и Жайрем

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Аннотация. В статье приводятся результаты исследований по комплексной переработке руд месторождений Шалкия и Жайрем, отличительной особенностью которых является не только не высокая степень флотируемости (из -за тесного взаимного прорастания рудных минералов цинка и свинца с нерудными минералами), но и высокое содержание в них (40-50%) кремнезема. Исследования проведены методами термодинамического моделирования с использованием программного комплекса HSC-6.0, основанного на принципе минимума энергии Гиббса, планированием второго порядка и электроплавкой в дуговой одноэлектродной печи сульфидных руд месторождений Шалкия и Жайрем (с отношением 1:1) совместно с углеродом (коксом) и железом (стальной стружкой). Определено влияние температуры и количества железа на равновесное распределение кремния, цинка, свинца состав кремнийсодержащего сплава и возгонов, содержащих цинк и свинец. Определены условия равновесного образования марочного ферросилиция с переходом в них от 60 до 85% кремния, не менее 99% цинка и 48-89% свинца в возгоны. Электроплавкой смеси руд Шалкия и Жайрем в присутствии 26% кокса и 18% стальной стружки получен ферросилиций марки FeSi45, а в присутствии 26% кокса и 38% железа -ферросилиций FeSi25. Возгоны электроплавки содержат 25.0-26.1% цинка и 10.5-11.8% свинца.

Ключевые слова: *свинцово-цинковые полиметаллические руды, ферросилиций, возгоны, термодинамическое моделирование, электроплавка.*

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