

Thermodynamic model and electric smelting of a mixture of cake from leaching of vanadium-containing quartzites with coal beneficiation tailings

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Abstract. The article presents the results of studies of obtaining a ferroalloy from a mixture of coal beneficiation tailings and cake from leaching of vanadium-containing quartzites (black shales) of the Balasauskandyk deposit. The study was carried out using the HSC-6.0 software package, using the Equilibrium Compositions module and the second-order rotatable planning method (Box-Hunter plan), followed by geometric optimization of equilibrium process parameters. Based on the studies on the interaction of coal beneficiation tailings and cake from leaching of vanadium-containing quartzites in the presence of iron, it was found that under equilibrium conditions, an increase in the ratio of coal beneficiation tailings to leaching cake, which allows increasing the degree of silicon extraction in FeSi, Si, is accompanied by undesirable development of SiC formation and positive decrease in the degree of gaseous SiO formation. In the temperature range of 1500–2000 °C, an increase in the tailings to the cake ratio from 0 to 1.7 increases the degree of silicon extraction into the alloy to 67.8% at 1900 °C and aluminum to 33.94% at 2000 °C. Ferrosilicon of the FeSi45 grade, with 51.1–66% Si extraction into it, is formed in the temperature range of 1703–1900 °C from a mixture of tailings and cake with their ratio from 0.38 to 1. By electric smelting of a mixture of tailings (containing 30–47% C) with cakes with a ratio from 1.0 to 0.32 together with steel cuttings, a ferroalloy – ferrosilicon of the FeSi45 grade with a content of 37–42% Si was obtained.

Keywords: cake leaching / coal tailings / thermodynamic modeling / electric smelting / ferroalloy

1 Introduction

In the modern world, environmental and resource conservation issues are of particular importance. Recycling metallurgical waste is not just a way to minimize its negative impact on the environment, but also an opportunity to expand the raw material base for various industries. The coal and metallurgical industries of Kazakhstan are the main sources of waste. In terms of coal reserves (34.2 billion tons), Kazakhstan ranks eighth in the world, and in terms of production – 11th [1–4]. As a rule, coals are beneficiated. When beneficiated, 0.3–0.4 tons of waste are formed per 1 ton of finished coal [5–8].

The composition of coal beneficiation tailings depends on the type of deposit and the type of beneficiation. For example, according to [9,10], flotation beneficiation tailings

contain 50–67 SiO₂, 10–47% C, 14–31 Al₂O₃, 1.0–2.0 CaO, 1.0–3.0 Fe₂O₃, 2.0–2.4 H₂O, 0.2–0.6 S, 0.7–3 MgO, 0.3–0.7 TiO₂.

Methods of processing and using coal beneficiation tailings are varied. Coal beneficiation tailings are mainly used in the construction of road foundations, embankments, filling mined-out spaces, and land reclamation [11–14]. Some coal beneficiation waste is used as an energy raw material by burning or gasification in fluidized bed furnaces, plasma furnaces, etc. For example, high-ash coal beneficiation waste in a dusty state is burned at power plants, thereby reducing fuel costs and reducing emissions of sulfur and nitrogen oxides into the environment [15–19]. Technologies were developed for using the organic component of coal beneficiation waste by pyrolysis to obtain liquid and gaseous products that are used to produce artificial liquid fuels, oils, ammonia synthesis, and lubricants [20–22].

Coal enrichment waste is successfully used for production of bricks, concrete and other building materials [23–29]. When burning of refractories, the organic

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Table 1. Chemical composition of starting materials, %.

Components	Composition, %									
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	V ₂ O ₅	MgO	H ₂ O	BaO	S	C
Coal beneficiation tailings	44.3	16.4	5.5	1.4	–	0.7	–	–	1.8	30
Quartzite leaching cake	72.5	1.3	1.7	1.5	0.16	0.4	3	0.15	0.2	19

components of coal enrichment tailings burn out, forming pores and reducing the density of the material, on this basis, the tailings are used as a combustible additive to raw materials in production of ceramic products: bricks, paving tiles, roofing tiles. Technologies were developed for the use of tailings in the production of artificial porous fillers (agloporite, expanded clay) and lightweight concrete based on them [30,31]. Options were proposed for using coal flotation beneficiation tailings as organomineral fertilizers, as well as a sorbent for wastewater treatment [32–36]. Bioleaching of coal beneficiation tailings with *Bacillus mucilaginosus* made it possible to increase the utilization rate of silicon from coal tailings to 93%, converting insoluble forms of silicon into compounds available to plants [37].

Tailings containing manganese, nickel, cobalt, vanadium, chromium, molybdenum, gold, iron and other valuable metals are an additional source of raw materials for metallurgical industry [38,39]. For example, a technology was proposed for processing waste from a coal beneficiating plant using gravity-magnetic technology, producing a gravity concentrate with an iron content of 25.3% and an extraction of 53.15%, and then using the wet magnetic separation method of iron-containing concentrate with a total iron content of 63.29% and secondary fuel-coal-containing concentrate with an ash content of 31.7% [40]. A technology for extracting alumina from coal beneficiation tailings containing a significant amount of aluminum oxide was proposed, which includes preparation of the charge, sintering of the waste with chalk and soda, leaching of the sinter, desiliconization of the aluminate solution, carbonization, filtering and washing of the aluminum hydroxide precipitate, and its thermal decomposition. The proposed technology showed the possibility of extracting 80–85% of the aluminum oxide contained in the material [41].

The possibility of extracting valuable metals such as manganese, nickel, cobalt, chromium, lead and zinc was proved by leaching various coal beneficiation tailings in a disintegrator. However, despite the high degree of extraction, the concentration of metals in the resulting solutions is quite low, which makes the process economically inexpedient [42–44].

The presence of carbon in coal beneficiation waste allows to consider the waste as potential raw materials for recovery metallurgical processes [45–48]. Moreover, the presence of volatiles in coal beneficiation tailings increases their reactivity. The increased specific resistance of tailings [49] allows to work with a lower electrode seat when smelting ferroalloys, reduces silicon losses with the gas phase.

In the metallurgical industry, waste, in addition to various sludges and slags, includes leaching cakes. Leaching cake is a by-product of hydrometallurgical processing, which is also a technogenic and valuable resource. The National Center for Complex Processing of Mineral Raw Materials of the Republic of Kazakhstan is developing a technology for hydrometallurgical processing of quartzites of the Bolshoi Karatau with the extraction of molybdenum and vanadium. The resulting cake contains up to 80% SiO₂, 15–16% C and 0.08–0.1% V [50–53], allows it to be classified as a promising raw material for smelting silicon ferroalloys.

The use of waste from processing plants as raw materials for metallurgy is a promising direction for industrial development, which allows to solve the problem of waste disposal, reduce the burden on the environment and production costs, and bring a significant economic effect. In particular, the replacement of coke in the production of ferroalloys with coal beneficiation tailings has significant economic potential: the cost of 1 ton of carbon in metallurgical coke (85% C) is 153,000 KZT (≈300 \$), while the cost of 1 ton of carbon in beneficiation tailings (30% C) is 8,400 KZT (≈17 \$). Thus, the use of beneficiation tailings as a source of carbon is approximately 18 times cheaper than coke.

The aim of the study was to determine the possibility of obtaining a ferroalloy from a mixture of coal beneficiation tailings (CBT) and cake from leaching of vanadium quartzites from the Balasauskandyk deposit (LC).

2 Material and methods

The study was conducted using the HSC-6.0 software package (developed by Outokumpu Research Oy, Finland) [54], using the Equilibrium Compositions module. The equilibrium degree of distribution of substances was calculated using the algorithm developed at “Metallurgy” chair, M. Auezov South Kazakhstan University [55]. The second-order rotatable planning (Box-Hunter plans) was also used, with subsequent geometric optimization of equilibrium process parameters [56–59].

Thermodynamic modeling was carried out in the temperature range from 500 to 2000 °C with a step of 100 °C at a pressure of 1 bar.

The chemical composition of the starting materials is given in Table 1. The work used cake from autoclave sulfuric acid leaching of vanadium-containing quartzites from the Balasauskandyk deposit and tailings from dry (gravity) beneficiation of low-ash long-flame coal from the Shubarkol deposit.

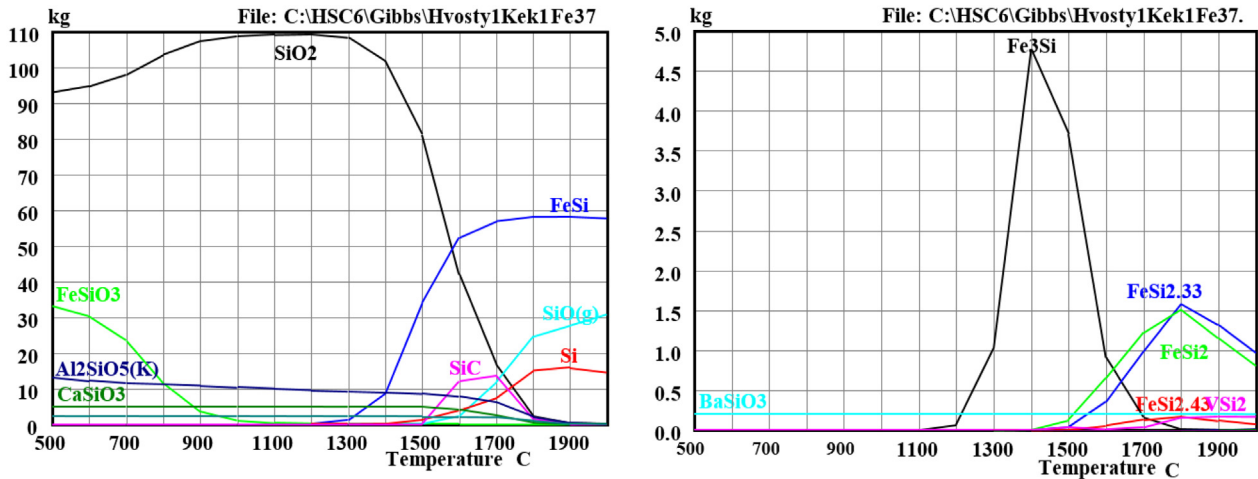


Fig. 1. The influence of temperature on the quantitative distribution of silicon in the $(\gamma=1)$ -Fe system.

The influence of temperature, the CBT/LC ratio (γ) on the equilibrium degree of element distribution (α , %) and their concentration in the alloy (C, %) was determined. Initially, the system (CBT):(LC) 1:1-iron was considered. The iron content in the system was 37.80% of the CBT and LC mixture mass.

The electric smelting of the leaching cake and coal beneficiation tailings mixture was carried out in a single-electrode arc furnace with a capacity of up to 15 kVA. The description and methodology of the electric smelting were described in detail in [60,61]. Before the smelting, the leaching cake and beneficiation tailings were pelletized with 3.7% bentonite clay and dried for an hour at a temperature of 120 °C. The silicon content in the alloy was determined by the pycnometric method, as well as by the atomic adsorption method using an AAS-1 device (Germany), as well as on a JSM – 6490LV scanning electron microscope with an INSAEnergy energy-dispersive microanalysis system (Japan).

3 Results and discussion

Figure 1 shows the primary information on the quantitative distribution of substances in the system under consideration, obtained by the HSC-6.0 software package.

It is evident that, depending on the temperature, the main substances in the system are SiO_2 , C, CO(g) , Fe, FeSi, Al_2O_3 , Al_2SiO_5 , FeSiO_3 , SiO(g) , CaSiO_3 , Si, SiC, MgSiO_3 , S, CaS, FeO, $\text{CS}_{2(g)}$, Fe_3Si , Al, FeSi_2 , $\text{FeSi}_{2.33}$, COS(g) , $\text{H}_{2(g)}$, $\text{S}_{2(g)}$, BaSiO_3 , CS(g) , Mg(g) , Fe_5Si_3 , $\text{CO}_{2(g)}$, MgO , Al(g) , $\text{H}_2\text{O(g)}$, $\text{FeSi}_{2.43}$, VSi_2 , V, $\text{VC}_{0.8}$, $\text{VC}_{0.88}$, VC, $\text{VC}_{0.9}$, CaO, Si(g).

Figure 2 shows information on the equilibrium distribution of silicon and aluminum, from which it is evident that silicon transforms into FeSi at a temperature of >1200 °C. The maximum of this transition (35.58%) occurs at 1900 °C. Silicon transforms into the elemental state starting at 1300 °C, increasing to 28.94% at 1900 °C. Silicon transforms into undesirable products – SiC in the range of 1500–1800 °C by 17.26% (1700 °C), and into SiO(g) starting at 1400 °C increases to 35.85% at 2000 °C.

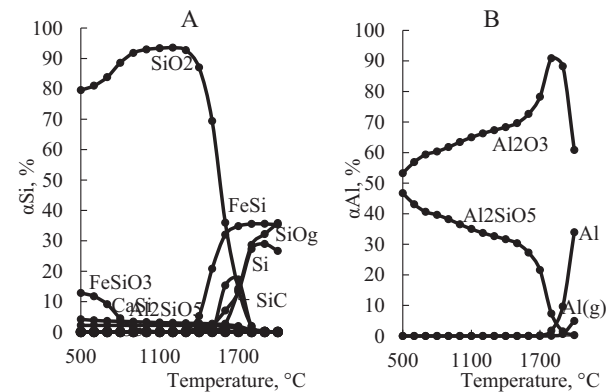


Fig. 2. The influence of temperature on the equilibrium distribution of silicon (A) and aluminum (B) in the $(\gamma=1)$ -Fe system.

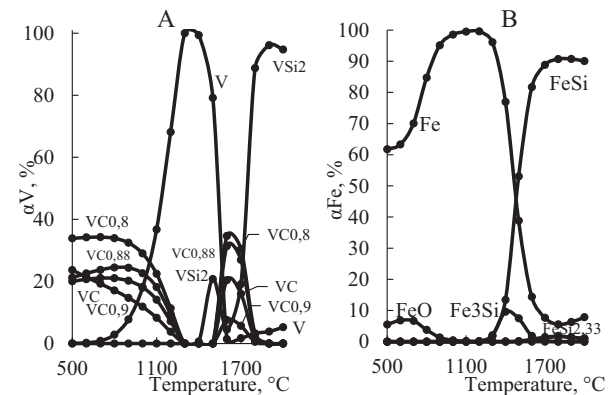


Fig. 3. The influence of temperature on the equilibrium distribution of vanadium (A) and iron (B) in the $(\gamma=1)$ -Fe system.

The transition of aluminum into the elemental state increases with increasing temperature from 1500 °C to 2000 °C up to 33.94%. Aluminum transforms into the gaseous state by 4.92% at 2000 °C.

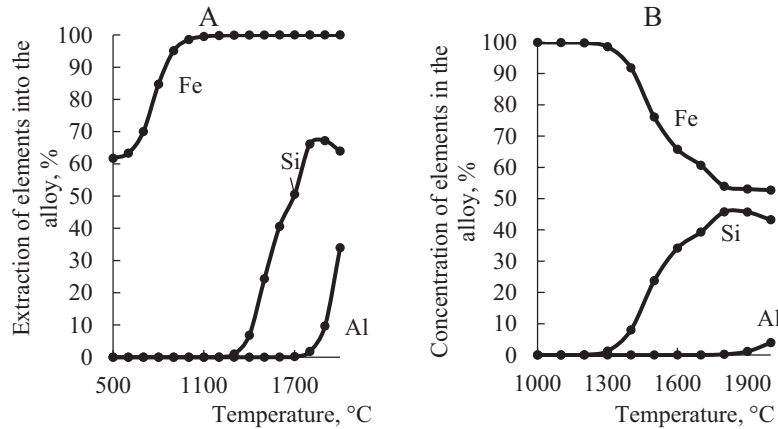


Fig. 4. The influence of temperature on the degree of extraction (A) and concentration (B) of elements in the alloy in the $(\gamma = 1)$ -Fe system.

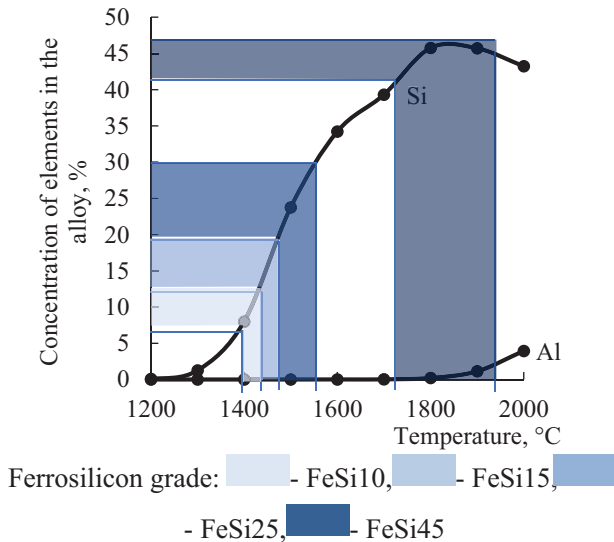


Fig. 5. Different ferrosilicon grades' formation areas.

It is evident from Figure 3 that in the temperature range of 500–1000 °C vanadium transforms into carbides: $VC_{0.8}$, $VC_{0.88}$, $VC_{0.9}$, VC . At 1300–1400 °C all vanadium is in the elemental state. Then, with an increase in the temperature to 1700 °C, VSi_2 , VC , $VC_{0.8}$, $VC_{0.88}$, $VC_{0.9}$ are formed.

The main part of iron at the temperatures above 1500 °C transforms into $FeSi$.

The influence of temperature on the elements' extraction degree into the alloy and the metals' concentration is shown in Figure 4. It is evident that the silicon extraction degree into the alloy $\Sigma FeSi$, Si , Fe_3Si , Fe_5Si_3 , $FeSi_{2.33}$, VSi_2 , V_5Si_3 is 67.18% at 1900 °C, and aluminum is 33.94% at 2000 °C. The silicon content in the alloy increases with increasing temperature, amounting to 45.76% at 1800 °C. The maximum concentration of aluminum in the alloy (3.94%) is observed at 2000 °C.

Figure 5 shows the areas of obtaining grade ferrosilicon [62], from which it is evident that at the temperature of 1400–1430 °C it is possible to form ferrosilicon of the $FeSi_{10}$

grade, at 1430–1475 °C – ferrosilicon of the $FeSi_{15}$ grade, at 1475–1550 °C – ferrosilicon of the $FeSi_{25}$ grade, at 1725–1935 °C – ferrosilicon of the $FeSi_{45}$ grade (with Al content of <2%). The extraction of Si into the alloy in this temperature range is 66.16–67.0%. At the temperature of 1935–2000 °C it is possible to form a Fe-Si-Al ligature containing 43.23% silicon and 3.94% aluminum.

To determine the optimal conditions for the ferroalloy formation from the mixture of CBT and LC, studies were conducted with γ from 0 to 2. In this case, both the effect of γ on the extraction of Si and iron silicides into the alloy, and on the negative degree of silicon transition into SiC and SiO (g), were determined.

Figure 6 shows the effect of γ and temperature on αSi into iron silicides SiC , $SiO(g)$, and Figure 7 – into Si .

From Figures 6 and 7 it is evident that an increase in γ leads to an increase in $\alpha Si(FeSi)$, $\alpha Si(Si)$, $\alpha Si(SiC)$, and decreases $\alpha Si(Fe_3Si)$, $\alpha Si(Fe_5Si_3)$, $\alpha Si(SiO)$. The dependence of $\alpha Si(FeSi_{2.33})$ is more complex. The maximum of the transition of Si to $FeSi_{2.33}$ (1.85%) is observed at 1900 °C. The main substances determining the behavior of silicon in the system at high temperatures are $FeSi$, SiC , SiO and Si . To reduce the phenomenon of SiC formation, the process should be carried out at 1800–1900 °C with $\gamma = 0$ –1 or at a higher temperature with $\gamma > 1.0$ (up to 2.0), and to reduce silicon losses with SiO , the process should be carried out with $\gamma = 1.7$ –2.0 at 1700–1800 °C. Based on the noted different nature of the influence of γ on the silicon extraction, the main characteristic of the process is the silicon extraction degree into the alloy in the form of ΣSi , iron and vanadium silicides ($\alpha Si_{(alloy)}$). Figure 8 shows the influence of γ and temperature on $\alpha Si_{(alloy)}$.

It is evident that at the temperature above 1800 °C, an increase in γ (especially from 0 to 1.7) allows increasing $\alpha Si_{(alloy)}$ (for example, at 1900 °C from 27.3 to 75.4%). γ has a positive effect on $\alpha Al_{(alloy)}$, increasing this indicator to 46.6–50.1% in the temperature range of 1900–2000 °C (Fig. 8B).

Figure 9 shows the change in the concentration of silicon and aluminum depending on the temperature and γ . It is evident that at a constant value of γ , the dependence of $CSi_{(alloy)}$ has an extreme character, which is associated with

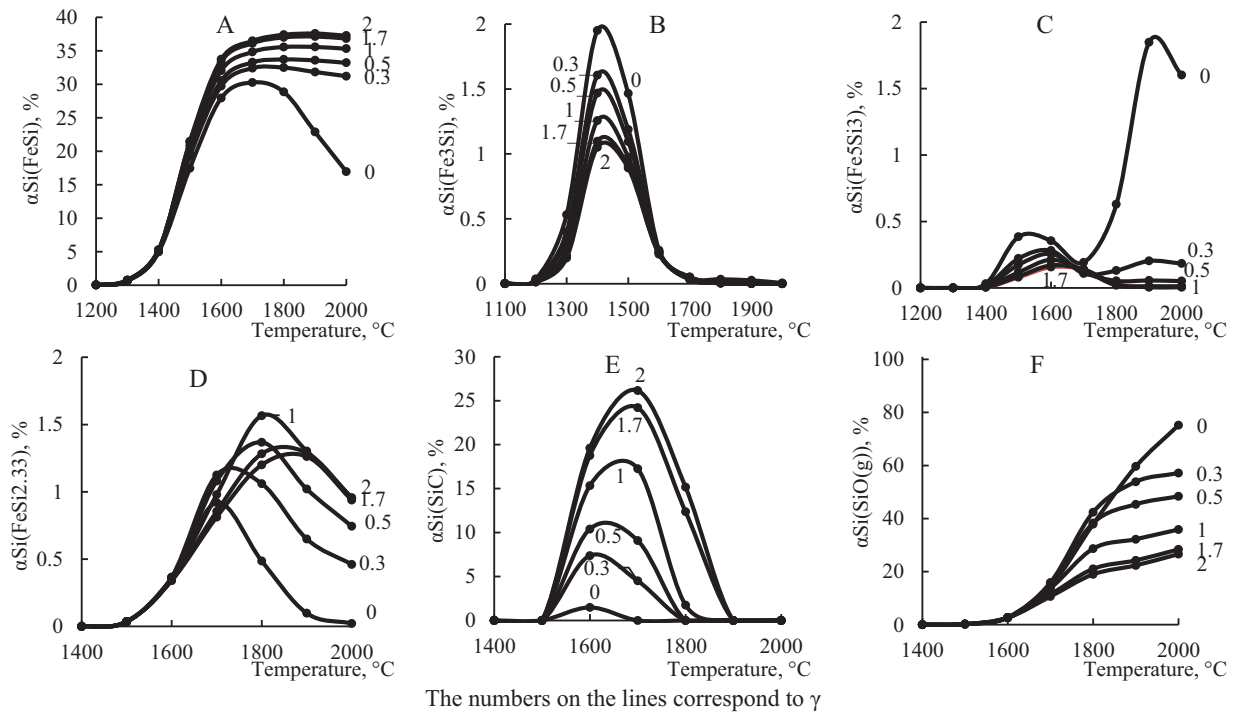


Fig. 6. The influence of γ and temperature on the silicon extraction degree in FeSi (A), Fe₃Si(B), Fe₅Si₃(C), Fe₂.33(D), SiC (E) and SiO(g) (F).

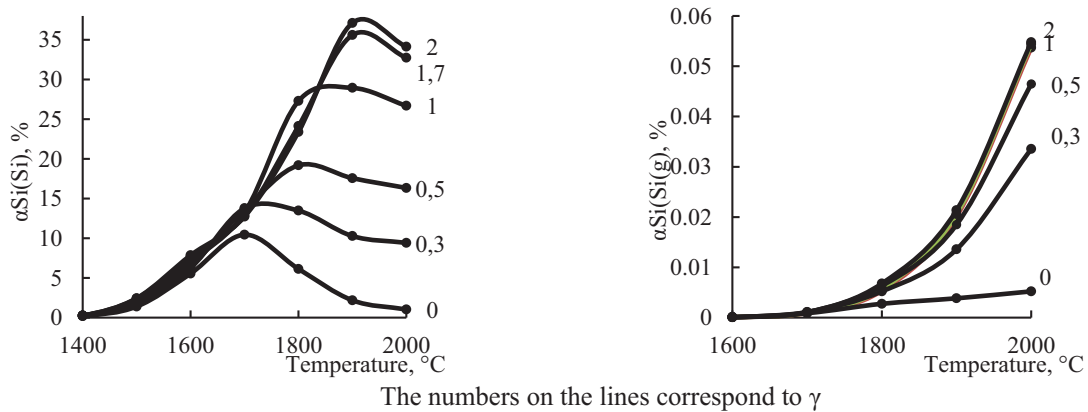


Fig. 7. The influence of γ and temperature on the silicon transition to the elemental state.

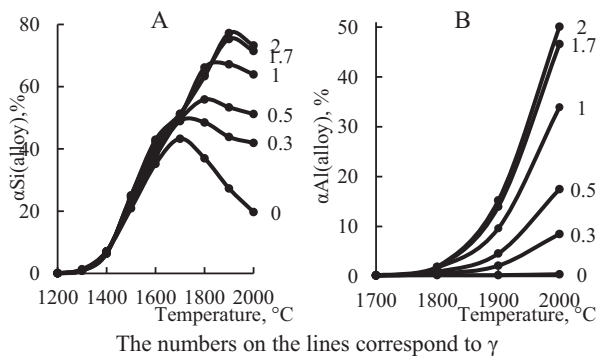


Fig. 8. The influence of γ and temperature on the extraction of silicon (A) and aluminum (B) into the alloy.

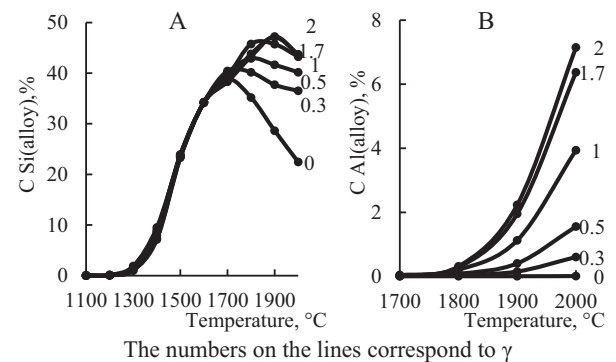


Fig. 9. The influence of γ and temperature on the concentration of silicon (A) and aluminum (B) in the alloy.

Table 2. Levels of factors and ranges of their variation in the study of the influence of temperature and the ratio of components on the production of ferroalloy.

Variables	Coded designation	Natural view	
		T, °C	γ
Basic level	0	1750	0.5
Variation interval	Δ	106.4	0.35
Upper level	+1	1856.4	0.85
Lower level	−1	1643.6	0.15
Upper “star” shoulder	+1.414	1900	1
Lower “star” shoulder	−1.414	1600	0

Table 3. Matrix for planning experiments and their results.

	Variables				Process parameters			
	Coded		Natural		$\alpha\text{Si}_{(\text{alloy})}$ studied, %	$\alpha\text{Si}_{(\text{alloy})}$ calculated, %	C Si _(alloy) studied, %	CSi _(alloy) calculated, %
	X ₁	X ₂	T, °C	γ				
1	−1	−1	1643.6	0.15	41.80	41.47	36.20	36.36
2	+1	−1	1856.4	0.15	38.80	40.46	34.00	35.50
3	−1	+1	1643.6	0.85	45.20	45.11	36.70	36.64
4	+1	+1	1856.4	0.85	61.00	62.91	44.00	45.28
5	1.414	0	1900	0.5	53.30	51.10	41.64	39.97
6	−1.414	0	1600	0.5	38.60	39.22	34.24	34.47
7	0	1.414	1750	1	60.00	59.04	43.80	43.23
8	0	−1.414	1750	0	41.20	40.59	37.00	36.12
9	0	0	1750	0.5	53.50	53.08	41.50	41.84
10	0	0	1750	0.5	53.80	53.08	42.60	41.84
11	0	0	1750	0.5	53.70	53.08	41.80	41.84
12	0	0	1750	0.5	52.00	53.08	41.00	41.84
13	0	0	1750	0.5	52.40	53.08	42.30	41.84

an increase in the degree of silicon loss with gaseous SiO with an increase in temperature. The maximum concentration of silicon in the alloy increases from 38.8 to 47.6% with an increase in γ from 0 to 2. This dependence is described by the equation:

$$CSi_{(\text{alloy})\max} = 38.61 + 8.616\gamma - 1.198\gamma^2 - 0.494\gamma^3 (R^2 = 0.988). \quad (1)$$

At 2000 °C, increasing γ from 0 to 2 increases $CAI_{(\text{alloy})}$ from 0.1 to 7.15%.

In order to determine the optimal equilibrium parameters of the influence of temperature and the ratio of raw components on $\alpha\text{Si}_{(\text{alloy})}$ and $CSi_{(\text{alloy})}$, further studies were conducted using the second-order rotatable planning method. The influence of temperature (T, °C) and the ratio of components (γ) on $\alpha\text{Si}_{(\text{alloy})}$ and $CSi_{(\text{alloy})}$ were carried out in the intervals given in Table 2, the planning matrix and the results of the studies are in Table 3.

Based on the data in Table 3, the following adequate second-order regression equations were obtained:

$$\alpha Si_{(\text{alloy})} = -988.887 + 1.2 \cdot T - 188.89 \cdot \gamma - 3.49 \cdot 10^{-4} \cdot T^2 - 13.33 \cdot \gamma^2 + 0.126 \cdot T \cdot \gamma, \quad (2)$$

$$CSi_{(\text{alloy})} = -565.028 + 0.7 \cdot T - 95.619 \cdot \gamma - 2.04 \cdot 10^{-4} \cdot T^2 - 8.816 \cdot \gamma^2 - 0.637 \cdot T \cdot \gamma. \quad (3)$$

The adequacy of the obtained equations is evidenced by the value of the Fisher criterion, the tabular value of which with an error of $\leq 5\%$ is less than 6.59. According to equations (1) and (2), the Fisher criteria are 6.43 and 6.51, respectively.

Using the obtained regression equations, 3D models and horizontal sections of the response surface were constructed using the MathCAD program (Fig. 10).

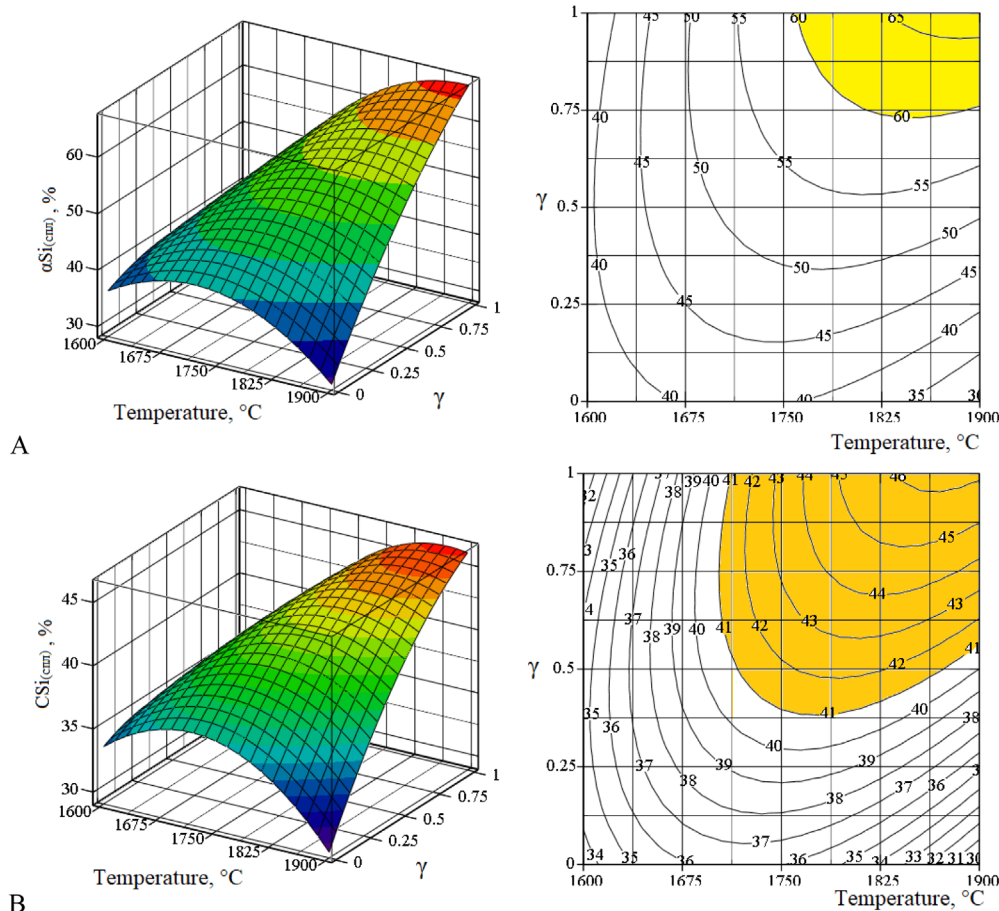
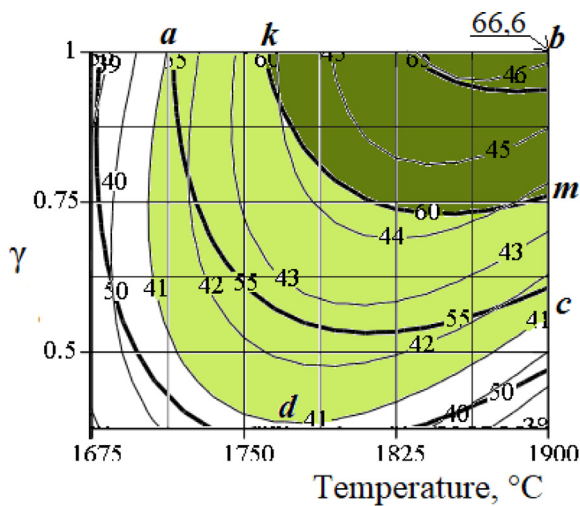


Fig. 10. The influence of γ and temperature on $\alpha\text{Si}_{(\text{alloy})}$ (A) and $\text{C Si}_{(\text{alloy})}$ (B).



Lines: (—) $\alpha\text{Si}_{(\text{alloy})}$, %; (---) $\text{C Si}_{(\text{alloy})}$, %

Fig. 11. Combined information on the influence of γ and temperature on the silicon extraction degree into the alloy and on the concentration of silicon in it.

It is evident from the figures that the silicon extraction degree into the alloy at 1900 °C is 66.6%. Using horizontal sections of the response surface, graphical optimization was

performed and the formation areas of the FeSi45 grade ferrosilicon were found. The FeSi45 grade ferrosilicon containing 41–47% silicon according to State standard 1415–93 is formed in the *abcd* area of Figure 11. Figure 11 shows a combined picture of the influence of temperature and γ on $\alpha\text{Si}_{(\text{alloy})}$ and $\text{C Si}_{(\text{alloy})}$ with the formation of the FeSi45 grade ferrosilicon. Table 4 shows the technological values of the selected areas.

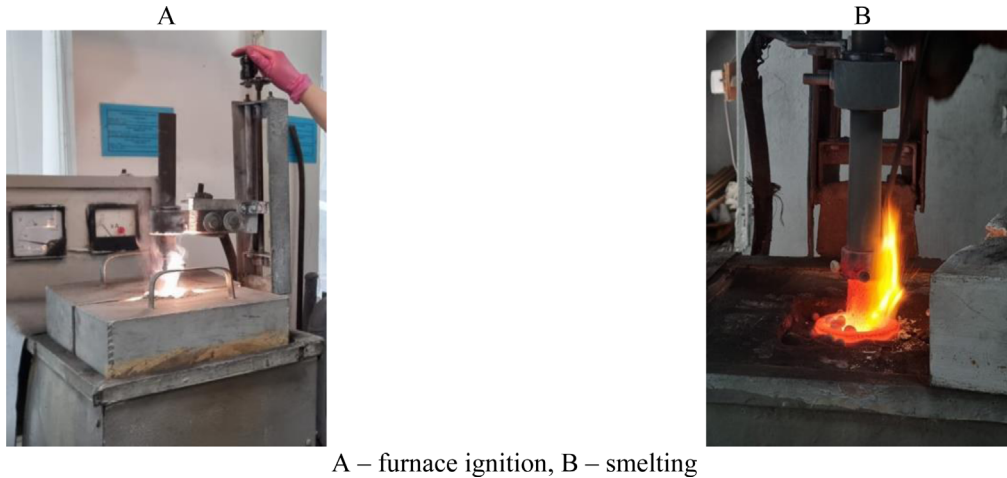
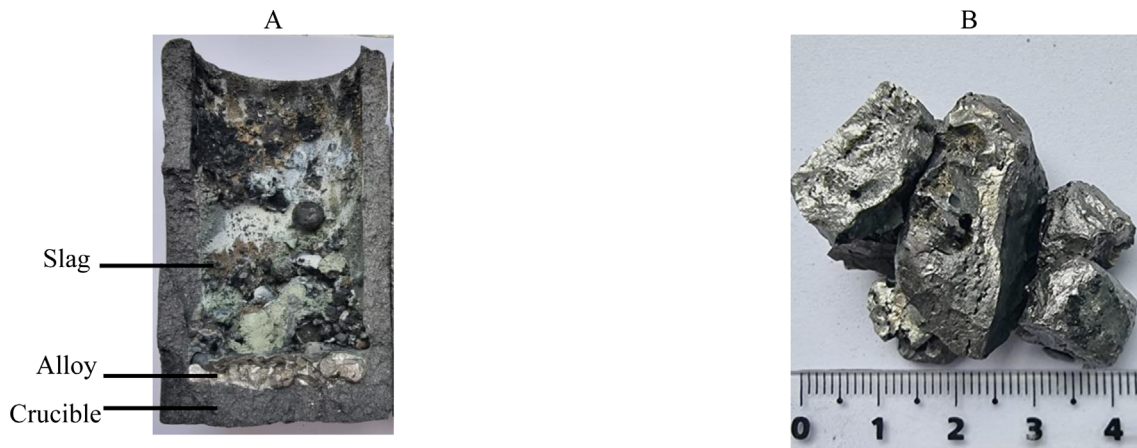
Ferrosilicon of the FeSi45 grade (41.0–44.5% Si) is formed in the temperature range of 1703–1900 °C, at γ 0.38–1, while the silicon extraction degree is 51.1–60.0%. Ferrosilicon of the FeSi45 grade with an increased silicon content from 43.7 to 46.2% can be obtained at 1760–1900 °C and γ 0.73–1.

By the electric smelting (Fig. 12) of the leaching cake and coal beneficiation tailings mixture with $\gamma=1$ in the presence of steel cuttings (97.6% Fe, 0.48% Si, 0.4% Mn, 1.5% C), an alloy with a content of 39–42% Si, corresponding to ferrosilicon of the FeSi45 grade, was obtained.

The second smelting was carried out with a mixture of cakes and coal gravity beneficiation tailings, which contained 48.7% C, 6.92% volatiles, 42.6% ash (39.8% SiO_2 , 0.4% CaO, 1.4% Fe_2O_3 , 0.8% Al_2O_3 , 0.78% H_2O , 1% S, 0.2% others). The ratio (γ) was 0.32 and the amount of steel cuttings was 50% of the mass of cake and coal beneficiation tailings. Figure 13 shows a crucible fracture

Table 4. Technological values of the areas of Figure 11.

Area	T, °C	γ	$\alpha\text{Si}_{(\text{alloy})}$, %	$\text{CSi}_{(\text{alloy})}$, %	Alloy grade
Akmcđ	1703–1900	0.38–1	51.1–60.0	41.0–44.5	FeSi45
kbm	1760–1900	0.73–1	60.0–66.6	43.7–46.2	

**Fig. 12.** Electric smelting of the mixture of quartzite leaching cake and coal beneficiation tailings.**Fig. 13.** Photograph of the crucible fracture (A) and crushed ferroalloy (B).

with ferroalloy and crushed ferroalloy. The smelted ferroalloy contains 37.8–44.4% silicon, which corresponds to ferrosilicon of the FeSi45 grade. The silicon extraction degree in the ferroalloy was 74.8%.

4 Conclusion

Based on the conducted studies on the interaction of coal beneficiation tailings and cake from leaching of vanadium-containing quartzites in the presence of iron, the following conclusions can be made:

- Under equilibrium conditions:
- Depending on the temperature and composition of the mixture, the products are FeSi , SiO_2 , C , $\text{CO}_{(\text{g})}$, Fe , Al_2O_3 , Al_2SiO_5 , FeSiO_3 , $\text{SiO}_{(\text{g})}$, CaSiO_3 , Si , SiC , MgSiO_3 , S , CaS , FeO , $\text{CS}_{2(\text{g})}$, Fe_3Si , Al , FeSi_2 , $\text{FeSi}_{2.33}$, $\text{COS}_{(\text{g})}$, $\text{H}_{2(\text{g})}$, $\text{S}_{2(\text{g})}$, BaSiO_3 , $\text{CS}_{(\text{g})}$, $\text{Mg}_{(\text{g})}$, Fe_5Si_3 , $\text{CO}_{2(\text{g})}$, MgO , $\text{Al}_{(\text{g})}$, $\text{H}_2\text{O}_{(\text{g})}$, $\text{FeSi}_{2.43}$, VS_{i2} , V , $\text{VC}_{0.8}$, $\text{VC}_{0.88}$, VC , $\text{VC}_{0.9}$, CaO , $\text{Si}_{(\text{g})}$;
- An increase in the ratio of coal beneficiation tailings to leaching cake, which allows increasing the silicon extraction degree in FeSi , Si , is accompanied by

undesirable development of SiC formation and a positive decrease in the degree of formation of gaseous SiO₂;

- In the temperature range of 1500–2000 °C, an increase in the ratio of tailings to cake from 0 to 1.7 increases the silicon extraction degree into the alloy to 67.8% at 1900 °C and aluminum to 33.94% at 2000 °C;
- Ferrosilicon of the FeSi45 grade, with the extraction of 51.1–66% silicon, is formed in the temperature range of 1703–1900 °C from the mixture of tailings and cake with their ratio from 0.38 to 1.
- During the electric smelting of the beneficiation tailings with cake (with the ratio from 1.0 to 0.32) in the presence of steel cuttings, the ferroalloy – ferrosilicon of the FeSi45 grade with the content of 37–42% Si is obtained.

The presented study is the initial stage of a comprehensive work aimed at creating an innovative technology for processing vanadium quartzite leaching cake. The results obtained allow to conclude that further research is promising. The next stage in the development of the technology will be experimental work on the use of other types of carbon-containing raw materials, determination of optimal process parameters and large-scale laboratory tests.

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Conflicts of interest

The authors have nothing to disclose.

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This article has no associated data generated and/or analyzed.

Author contribution statement

Conceptualization, A. D. Badikova and V. M. Shevko; Methodology, V. M. Shevko; Software, V. M. Shevko; Validation, A. D. Badikova and V. M. Shevko; Formal Analysis, A. D. Badikova and V. M. Shevko; Investigation, A. D. Badikova; Resources, V. M. Shevko and D. K. Aitkulov; Data Curation, V. M. Shevko; Writing – Original Draft Preparation, A. D. Badikova; Writing – Review & Editing, A. D. Badikova, M. Shevko and D. K. Aitkulov; Visualization, A. D. Badikova; Supervision, V. M. Shevko and D. K. Aitkulov; Project Administration, A. D. Badikova; Funding Acquisition, D. K. Aitkulov.

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