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Computer thermodynamic modeling of obtaining ferroalloys from a mixture of leaching tailings of oxidized copper ores

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Abstract. The article presents the results of computer thermodynamic modeling and experiments on the production of ferroalloys of the production of ferroalloys from a mixture of tailings for sulfuric acid leaching of oxidized copper ores from the Almaly, Ayak-Kodzhan, Aktogay, Kounrad, Shatyrkol deposits, containing (%): 65.2SiO_2; 14.2Al_2O_3; 7.4Fe_2O_3; 2.4K_2O; 2.7Na_2O; 6.6CaO; 2.8MgO; 0.2CuO. The simulations were carried out using the HSC-6.0 software package based on the Gibbs minimum energy principle, as well as the research planning method using a rotatable second-order plan (the Box-Hunter plan). Experiments on melting a mixture of tailings were carried out on the Tamma furnace in isothermal mode. The influence of temperature and the amount of carbon on the equilibrium degree of distribution of silicon, aluminum and the concentration of these metals in the alloy was determined. Based on the results obtained, it was found that the equilibrium interaction of a mixture of heap leaching tailings of copper ores with carbon and iron occurs with the formation of FeSi, $FeSi_2$, $FeSi_{2.33}$, Fe_5Si_3, $FeSi_{2.43}$, Fe_3Si, Si, SiO_2, Al, SiC, $CaSiO_3$, Al_2SiO_5, $MgSiO_3$, K_2SiO_3, Na_2SiO_3, Cu, CO. An increase in iron from 30 to 50% of the mass of the mixture of leaching tailings and temperatures from 1600 to 2000ºC increases the degree of extraction into the silicon alloy to 83.2%, and reduces the concentration of silicon in it from 40-41.41% (at 1800ºC) to 30-31%, aluminum at 2100ºC from 8.3% to 5.5%. Ferrosilicon of the $FeSi_{45}$ brand with the extraction of 74-81.9% Si from it is formed at 1780-1910ºC, 30% iron and 34% carbon, and the $FeSi_{25}$ brand with the extraction of 70-76% Si into it is formed in the temperature range of 1660-1730ºC in the presence of 43.5-50% iron. Determines the influence of temperature 1000-2100ºC and iron. To achieve high (≥80%) silicon in the alloy, a temperature of at least 1800ºC and an 80-minute duration of the process are required.

Keywords: *oxidized copper ores, leaching tailings, thermodynamic modeling, rotatable planning, electrofusion, ferrosilicon.*

1. Introduction

The main methods of processing oxidized and mixed copper ores are flotation and leaching. It is shown that in order to improve the flotation of this category of ores, they must be pre-sulfidated using sulfur, hydrogen sulfide, sodium sulfides of barium, aluminum, polysulfides and sodium thiosulfate, which make it possible to convert copper oxide minerals into floatable forms up to 95% copper [1]. Low rates of flotation concentration of copper oxide ores are due to the presence of oxide minerals in the ores.

Various reagents are used to leach oxidized ores: acids (hydrochloric, sulfuric, nitric), alkalis, cyanide and ammonia solutions [2].

It is shown that hydrochloric acid and its mixture with nitric acid, because of the gold and silver used for leaching, because of their high price, it is not economically feasible to leach copper. In addition, hydrochloric acid belongs to aggressive difficult-to-regenerate solvents [3, 4, 5]. Ammonia leaching has no great prospects due to the toxicity of ammonia [6]. Cyanide solutions [7], due to their high toxicity (0.3 mg/m^3) and high NaCN consumption, also have no prospects in the technology of extracting copper from ore. Recently, there have been publications on the leaching of mixed ores with a solution of ammonium sulfate [8] and an organic agent (an aqueous solution of tricarbonate acid together with citric acid) to obtain a solution of copper nitrate [9]. Currently, the main method of heap leaching in copper oxidized and mixed ores is sulfuric acid leaching [10-17, 2].

The processing of heap leaching solutions is currently carried out using the so-called SX-EW technology, which consists in the selective extraction of copper from the solution into an organic phase (extractant) during liquid extraction, followed by its electrolytic deposition from the re-extract. The main advantages of this technological scheme for processing solutions are: low investment and production costs, high purity of the final metal – cathode copper (from 99.999 to 99.9995 copper). In recent years, about 16-19% of cathode copper has been produced worldwide using heap leaching -liquid extraction – electrolysis (SX-EW) technology [18-21]. In Kazakhstan, which has large reserves of copper [22], this method is used to extract copper from various deposits [23]. Flotation and leaching of oxidized copper ores have an obvious disadvantage - the formation of multi-tonnage waste in the form of flotation tailings and sulfuric acid leaching tailings, with which silicon, iron, aluminum is lost. Therefore, the degree of integrated use of copper ore is quite low.

In contrast to the known methods of processing such a category of raw materials, which provide for the preferential extraction of the main element, it is necessary to search for innovative technologies that ensure the complex processing of raw materials with the extraction of not only non-ferrous metals from raw materials, but also non-metallic components and iron [22].

The purpose of this work was to determine the conditions for the formation of ferrosilicon from a mixture of sulfuric acid leaching tailings of several oxidized copper ores of Kazakhstan.

2. Materials and methods

Thermodynamic modeling was carried out using the HSC – 6.0 software package based on the Gibbs minimum energy principle [24]. On the basis of the algorithm developed at M. Auezov SKU [25], we calculated the equilibrium degree of the distribution of elements and the concentration of elements in the alloy. The method of thermodynamic modeling was combined with rotatable planning of the second plan (the Box - Hunter plan) with the derivation of regression equations, the construction of volumetric and planar images [26, 27, 28]. The action of silicon, aluminum and the concentration of metals in the alloy. This method, due to its high information capacity, was used by us in the processing of various natural and man-made raw materials [29-31].

The studies were carried out with a mixture of heap leaching of five Kazakhstan oxidized ores, the composition of which is shown in Table 1.

Table 1. Chemical composition of leaching tailings of oxidized copper ores of Kazakhstan

Ore deposit tailings	Content, %							
	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	CuO	Fe_2O_3
Ayak-Kodzhan	63.0	13.6	3.2	4.8	3.7	1.6	0.3	9.8
Aktogay	70.0	16.0	5.5	1.0	3.3	3.6	0.1	2.5
Kounrad	71.9	12.9	3.8	3.0	2.9	2.7	0.1	5.6
Almaly	69.9	15.9	2.8	2.2	2.6	3.6	0.2	2.6
Shatyrkol	48.7	15.2	14.5	3.0	1.0	0.6	0.2	16.8

The mixture of heap leaching tailings from five ores contained in equal amounts, mass %: 65.2 SiO_2; 14.2 Al_2O_3; 7.4 Fe_2O_3; 2.4 K_2O; 2.7 Na_2O; 6.6 CaO; 2.8 MgO; 0.2 CuO. In modeling, of temperature (from 1000 to 2100ºC), the amount of iron (from 30 to 50% of the mass of heap leaching) on the equilibrium degree of distribution of silicon, aluminum, the concentration of elements in alloys at a pressure of 1 bar was determined. The amount of carbon was constant and amounted to 34% by weight of the heap leach. During melting, the influence of temperature and time on the degree of silicon extraction into the alloy was determined. The silicon content in the alloy was determined by thermometric method [32].

When conducting research on the Tamman furnace, the furnace was preheated to the required temperature. Temperature control was carried out with a BP-5/20 thermocouple. The heating element was a graphite pipe (d = 8 cm, h = 70 cm, thickness = 0.8). A graphite crucible (d = 5 cm, h = 10 cm) with a charge was lowered into the furnace (on a graphite stand) and kept in it for a certain time. Then it was quickly hooked onto the cross beam of the crucible with a steel hook and removed from the furnace. The crucible was broken after cooling (Figure 1).

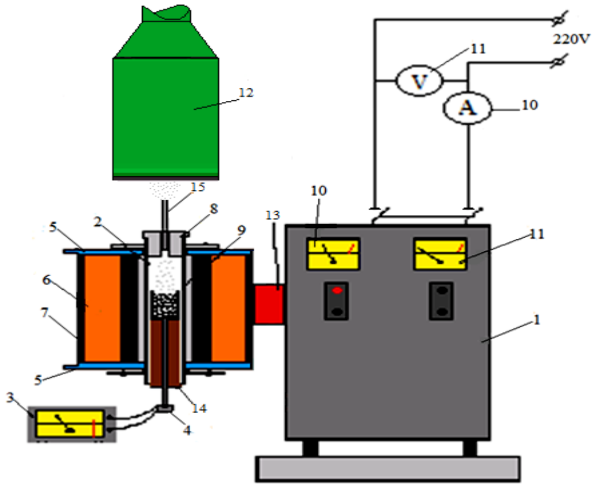


Figure 1. Installation diagram with Tamman furnace: 1 - transformer, 2 - graphite pipe heater, 3 - millivoltmeter, 4 - thermocouple BP, 5 - upper and lower covers with water cooling, 6 - isolation, 7 - casing, 8 - stopper, 9 - graphite crucible with charge, 10 - ammeter, 11 - voltmeter, 12 - exhaust hood, 13 - copper busbar, 14 - the stand is made of refractory material, 15 - quartz tube

3. Results and discussion

It was found that the interaction in the systems, depending on the temperature and the amount of iron, occurs with the formation of 17 substances: FeSi, $FeSi_2$, $FeSi_{2.33}$, Fe_5Si_3, $FeSi_{2.43}$, Fe_3Si, Si, SiO_2, Al, SiC, $CaSiO_3$, Al_2SiO_5, $MgSiO_3$, K_2SiO_3, Na_2SiO_3, Cu, CO. The quantitative (kg) distribution of SiO_2 reduction products and substances containing aluminum is shown in Figure1. Iron silicides (FeSi, Fe_3Si) begin to form at 1200ºC, Fe_5Si_3 at Si at 1400ºC, SiOg - at 1500ºC, SiC at 1600ºC, Al - at 1700ºC, and Alg – at 1900ºC.

Figure 2 shows information about the equilibrium degree of distribution of silicon αSi, aluminum αAl. Figure 2 shows the distribution of silicon and aluminum in the system under study, from which it follows that silicon in the system is in the form of SiO_2, FeSi, Si, $CaSiO_3$, SiOg. Initially, $CaSiO_3$, is formed in the system, it can be seen that during the reduction, the main part of silicon passes into FeSi, Si and SiOg. It can be seen that during the reduction, the main part of silicon passes into FeSi, Si and SiOg. Moreover, with an increase in the amount of iron, the degree of silicon transition in FeSi and Fe_3Si, increases, and in Si and SiOg – it decreases. Thus, at 1800ºC the α_{Si}(FeSi) increases from 50.3 to 70.2%, and in Si it decreases from 23.0 to 11.1%. In the system under consideration, Al_2SiO_5 is formed already at 1000ºC. Then silicon is reduced from it at a temperature of >1200ºC with the formation of secondary Al_2O_3, from which aluminum is formed.

As the temperature increases, the degree of transition of silicon to $CaSiO_3$ decreases. he degree of transition of silicon to SiO_2 with increasing temperature, silicon extraction decreases from 70.90 to 1.01%.

The influence of temperature on the equilibrium degree of distribution of elemental aluminum begins at 1700ºC, with an increase in temperature, the degree of aluminum extraction reaches 71.98%. Where the amount of iron is 50%, aluminum turns into elemental aluminum at 1800ºC temperature, the degree of extraction is 2, 8.2%. The maximum degree of extraction of aluminum in the elemental state is 67.32%, at 2100ºC temperature.

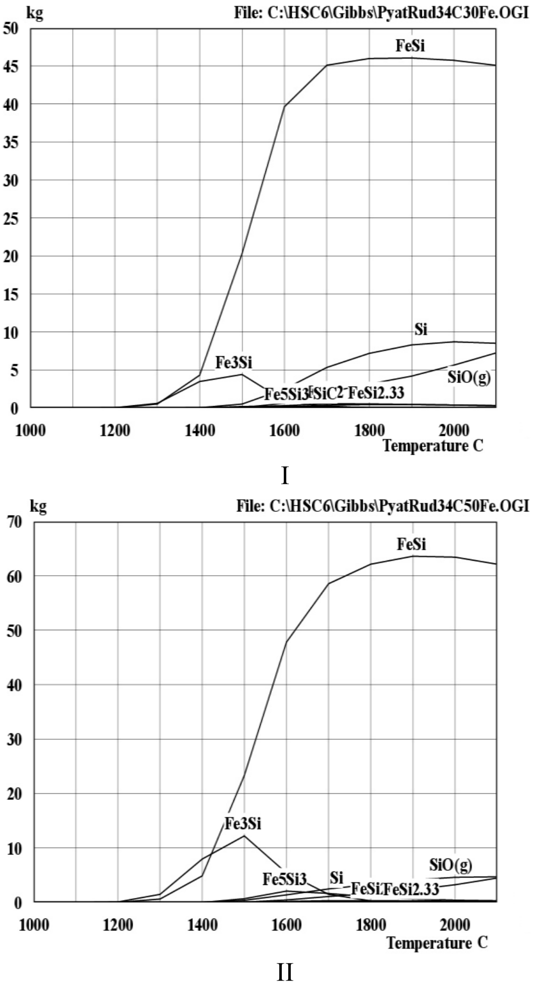


Figure 1. The effect of temperature and iron on the quantitative (kg) of SiO_2 reduction products. Amount of iron: I - 30 %, II - 50 %

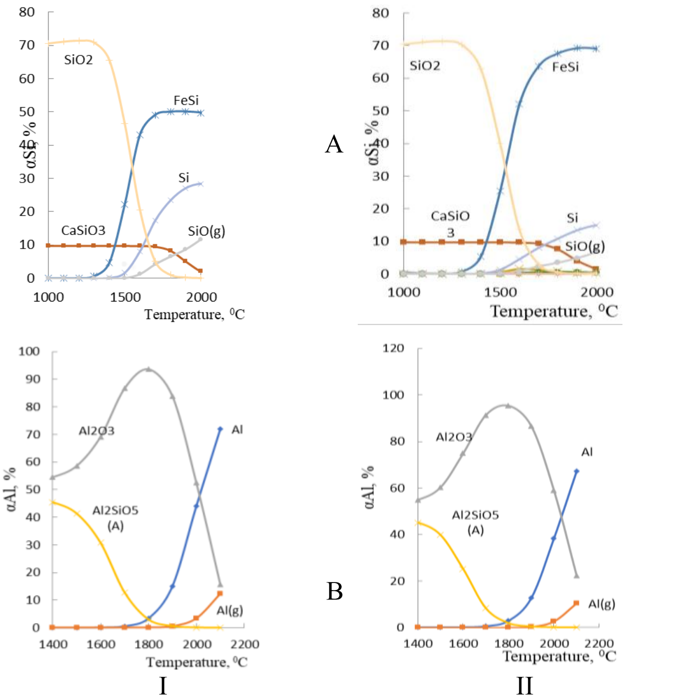


Figure 2. Influence of temperature and amount of iron and the equilibrium degree of distribution of silicon (A), aluminum (B): amount of iron I - 30%, II - 50%

Figure 3 shows information on the effect of temperature and iron on α_{Si}(alloy) and α_{Al}(alloy), from which it follows that an increase in the iron charge makes it possible to increase the degree of silicon extraction into the alloy in the temperature range 1600-2000ºC to 81.5%, and aluminum at 2000ºC - to 45.2% where the amount of iron is 50%. An increase in the iron charge increases the degree of silicon extraction into the alloy in the temperature range of 1600-2000ºC to 78%, and aluminum at 2000ºC - to 30%, where the amount of iron is 30%.

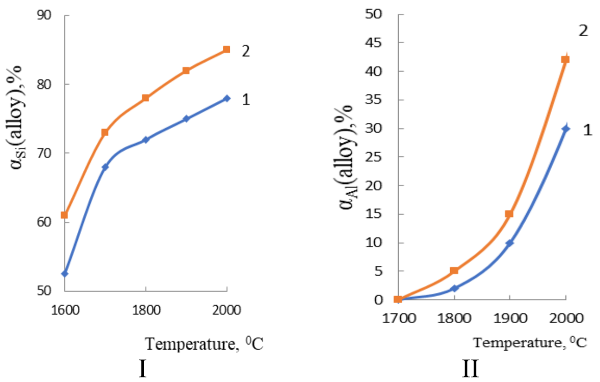


Figure 3. Influence of temperature and iron on the equilibrium distribution of silicon (1) and aluminum (2): amount of iron I - 30%, II - 50%

With an increase in the amount of iron from 30 to 50%, the concentration of silicon in the alloy decreases at 1800-1900ºC from 40-41.4% to 30-31% and aluminum at 2000ºC from 5.8 to 3.1% (Figure 4).

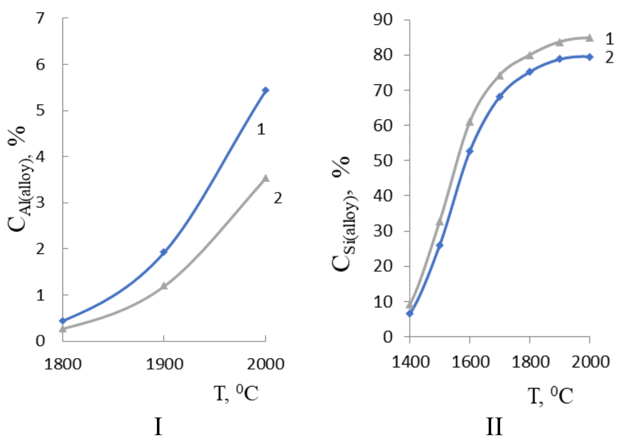


Figure 4. Influence of temperature and iron. Amount of iron: I – 30 %, II – 50 %

Bearing in mind the opposite nature of the effect of iron on α_{Si}(alloy) and C_{Si}(alloy), further studies were carried out by the method of rotatable second-order planning followed by geometric optimization. The planning matrix and research results are shown in Table 2.

Using the data in Table 1, the regression equations were established:

$\alpha_{Si}(alloy) = f$ (T, Fe) and CSi(alloy)=f(T, Fe)

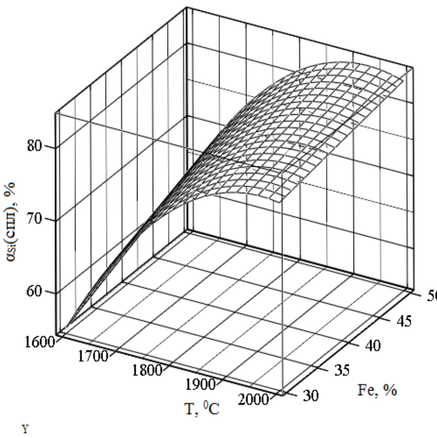
$$\alpha_{Si}(alloy) = -692.47 + 0.764T + 1.318 \cdot Fe - 5.78 \cdot 10^{-4} \cdot Fe \cdot T - 1.89 \cdot 10^{-4} \cdot T^2 - 1.43 \cdot Fe^2 \cdot 10^{-4} \quad (1)$$

$$C_{Si}(alloy) = -182.6 + 0.276\,T - 1.848 \cdot Fe^{-1} \cdot 10^{-4} \cdot FeT - 7.1 \cdot 10^{-4} \cdot T^2 + 1.91\,Fe^2 \cdot 10^{-2} \quad (2)$$

Table 2. Planning matrix and research results for obtaining ferroalloy from a mixture of leaching tailings of oxidized copper ores

N	Variables				α_{Si} (alloy), research., %	α_{Si} (alloy), calculate., %	C_{Si} (alloy), research, %	C_{Si} (alloy), calculate, %
	Encoded		Natural					
	X_1	X_2	T, ^{0}C	Fe, %				
1	-1	-1	1658	33	64.6	63.6	34.6	34.9
2	+1	-1	1942	33	80.2	80.9	40.0	40.0
3	-1	+1	1658	47	69.8	68.5	28.6	28.2
4	+1	+1	1942	47	83.1	83.4	33.6	32.9
5	1.414	0	2000	40	82.6	81.7	34.6	35.0
6	-1.414	0	1600	40	57.3	58.8	28.3	28.2
7	0	1.414	1800	50	80.0	80.6	30.8	31.5
8	0	-1.414	1800	30	75.2	75.3	41.6	41.3
9	0	0	1800	40	78.5	77.9	35.1	34.5
10	0	0	1800	40	77.8	77.9	34.0	34.5
11	0	0	1800	40	78.0	77.9	34.8	34.5
12	0	0	1800	40	78.4	77.9	34.5	34.5
13	0	0	1800	40	77.0	77.9	34.2	34.5

The obtained regression equations are adequate since the calculated values of the Fisher criterion, respectively 6.49 and 3.119, are less than its tabular value – 6.59 [26]. Volumetric and planar images of changes in the degree of silicon extraction into the alloy and the concentration of Si in it (Figures 5,6).



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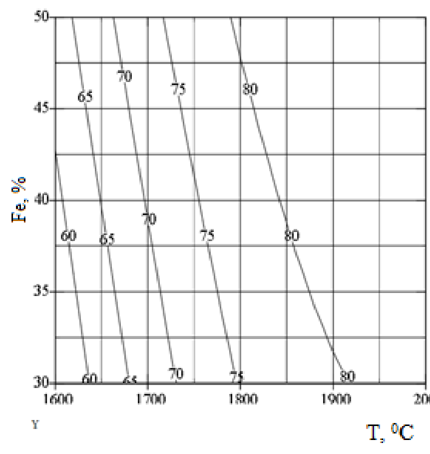
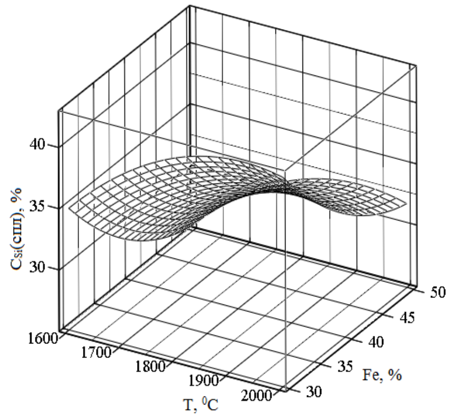


II

Figure 5. Volumetric (I) and planar (II) images of the effect of temperature and iron on the degree of silicon extraction into the alloy



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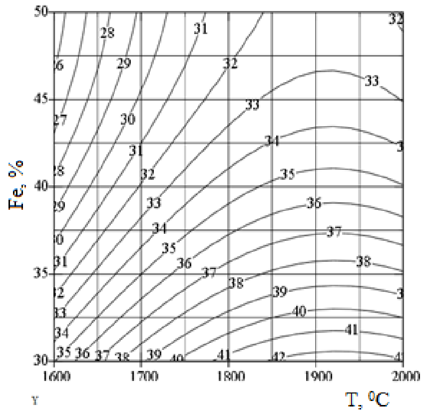

II

Figure 6. Volumetric (I) and planar (II) images of the influence of temperature and iron on the concentration of silicon in the alloy

It can be seen that the degree of silicon extraction into the alloy varies from 59.2 to 83.2%, and the silicon concentration varies from 25.6 to 42.4%. According to the silicon content, the resulting ferroalloy has the grades $FeSi_{25}$ and $FeSi_{45}$ [33].

Figure 7 shows the combined information about the change of α_{Si}(alloy) and C_{Si}(alloy). It can be seen that medium siliceous ferrosilicon is formed at a small (30-31.7%) amount of iron at 1600-1730ºC, and low siliceous - at 37-55% Fe at a lower temperature. Table 2 shows the technological parameters at the boundary points of Figure 7.

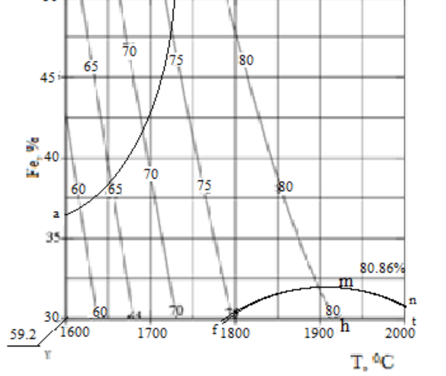

Figure 7. Combined information on the effect of temperature and iron on the technological parameters of obtaining ferroalloy from a mixture of tailings. Amount of iron I - 30%, II - 50%. ***$\alpha_{Si(alloy)}$ - (——), $C_{Si(alloy)}$ - (▬),***

Table 3. Technological parameters at the boundary points of Figure 7

The point in Figure 7	T, °C	Fe, %	α_{Si} (alloy), %	C_{Si} (alloy), %	α_{Al} (alloy), %	C_{Al} (alloy), %
a	1600	37.0	58.3	30.0	-	-
b	1600	50.0	63.6	25.6	-	-
x	1660	50.0	70.0	28.0	-	-
y	1720	50.0	75.0	29.7	<0.2	-
c	1730	50.0	75.2	30.0	<0.2	-
r	1725	48.3	75.0	30.0	<0.2	-
d	1780	43.5	70.0	30.0	2.9	-
t	2000	30.0	81.5	42.0	45.3	5.8
m	1925	31.7	80.6	41.0	26.5	2.1
n	2000	30.8	81.9	41.0	46.0	4.9
h	1930	30.0	80.3	42.4	23.2	2.6
f	1780	30.0	74.0	41.0	5.6	-

It follows from Figure 7 of Table 3 that the formation of ferrosilicon of the $FeSi_{45}$ brand occurs in the fmnth region at α_{Si}(alloy) from 74.0 to 81.9% in the temperature range of 1780-2000ºC in the presence of 30-31.7% iron. In the abc region, low siliceous ferrosilicon $FeSi_{25}$ is formed with a silicon content of 25.6 to 30%. In this area there is a narrow ycr region, in which the α_{Si}(alloy) is quite high - 75-75.2. In the xycrd plane, the α_{Si}(alloy) is somewhat smaller and is 70-76%. The temperature in this area is 1660-1730ºC, and the amount of iron is 43.5-50%. Ferrosilicon of the $FeSi_{25}$ brand is also formed in the abcd plane. The temperature in this area decreases to 1600ºC, however, the α_{Si}(alloy) also decreases to 58.3%.

To obtain Fe-Si-Al ligature containing 2.1-5.8% Al, 41.0-42.4% Si a temperature of 1025-2000ºC and the presence of 30.0-31.7% iron in the charge is required. It should be noted that the concentration of copper in alloys is 0.17-0.29%. According to this indicator, ferroalloy is similar to industrial ones, in which the copper content is 0.14-0.36% [34].

Figure 8 shows the results of experiments on the effect of temperature and time on the degree of silicon extraction into the alloy. The research was carried out with a charge containing 35% coke and 30% steel chips by weight of the tailing mixture (i.e. 60% tailing mixture of 21% coke and 19% steel shavings).

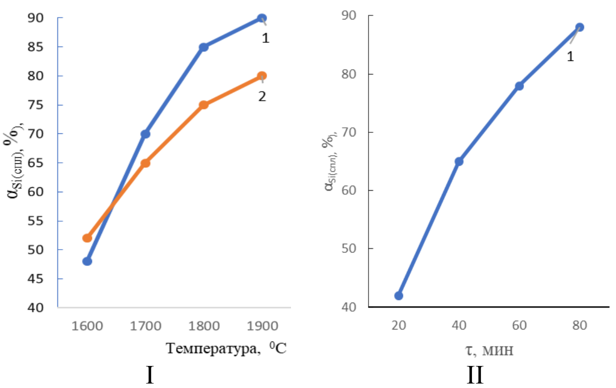

Figure 8. Influence of temperature (A) and time (B) on the degree of silicon extraction into the alloy and mixtures of sulfuric acid leaching tailings of oxidized copper ores: 1-according to the experimental, 2- on thermodynamic modeling

Figure 8 shows that in order to achieve a high Figure 8 shows that in order to achieve a high (>80%) silicon extraction into the alloy, a temperature of more than 1700ºC and a melting duration of at least 80 minutes are required.

A comparison of the results of thermodynamic modeling with the results of experiments on melting a mixture of tailings (Figure 8(I), Lines 1 and 2) shows that at a temperature of more than 1630ºC (when the rest of the silicon reduction occurs), the degree of silicon extraction according to experiments is higher than in thermodynamic modeling. (Moreover, this difference increases with increasing temperature). This pattern is explained by the fact that during thermodynamic modeling, part of Si is lost with gaseous SiO (Figure 2). During electric melting, gaseous SiO is also formed. However, in the furnace, due to the presence of a solid charge in the upper part of the crucible, SiOg is deposited in the charge and does not go beyond the crucible, returning with the charge to melting.

In thermodynamic modeling, the filter layer of the charge is not considered. Therefore, the extraction of Si into the alloy during melting is greater than during modeling.

4. Conclusions

Based on the results obtained on thermodynamic forecasting and experiments on the interaction of a mixture of heap leaching tailings of copper ores with carbon and iron, the following conclusions can be drawn:

1. In equilibrium conditions:

- interaction in the system occurs with the formation of FeSi, $FeSi_2$, $FeSi_{2.33}$, Fe_5Si_3, $FeSi_{2.43}$, Fe_3Si, Si, SiO_2, Al, SiC, $CaSiO_3$, Al_2SiO_5, $MgSiO_3$, K_2SiO_3, Na_2SiO_3, Cu, CO.
- an increase in iron from 30 to 50% of the mass of the tailing mixture and a temperature from 1600 to 2000ºC makes it possible to increase the degree of extraction into the silicon alloy to 81.5%, while the concentration of silicon in the alloy decreases from 40-41.41% to 30-31%, and aluminum at 2000ºC from 5.8% to 3.1%.
- ferrosilicon of the $FeSi_{45}$ brand with the extraction of 74-81.9% Si into it is formed at 1780-1910ºC, 30% iron and 34% carbon.
- ferrosilicon of the brand $FeSi_{25}$ with the extraction of 70-76% from it is formed in the temperature range of 1660-1730ºC in the presence of 43.5-50% iron.
- Fe-Si-Al ligature containing 2.1-5.8% Al, 41-42.4% Si is formed at 1925-2000ºC in the presence of 30-31.7% iron.

2. To achieve the degree of silicon extraction into the alloy ≥ 80% the melting of the tailing mixture should be carried out for at least 80 minutes at a temperature of at least 1800ºC.

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Тотыққан мыс кендерін шаймалаудың кек қоспасынан ферроқорытпаларды компьютерлік термодинамикалық модельдеу және эксперименттік өндіру

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[2]*Қазақстан Республикасының минералдық шикізатты кешенді қайта өңдеу жөніндегі ұлттық орталығы, Алматы, Қазақстан*

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Аңдатпа. Мақалада Алмалы, Аяк-Қожан, Ақтоғай, Қоңыррад, Шатыркөл кен орындарының тотыққан мыс кендерін күкірт қышқылды сілтілеу кектерінің қоспасынан ферроқорытпаларды алу бойынша компьютерлік термодинамикалық модельдеу және эксперименттердің нәтижелері келтірілген (%): 65.2SiO_2; 14.2Al_2O_3; 7.4Fe_2O_3; 2.4K_2O; 2.7Na_2O; 6.6CaO; 2.8MgO; 0.2CuO. Модельдеу Гиббстің минималды энергетикалық принципіне негізделген HSC-6.0 бағдарламалық кешенінен, сондай-ақ екінші ретті айналмалы жоспарды (бокс-Хантер жоспары) қолдана отырып зерттеуді жоспарлау әдісін қолдана отырып жүргізілді. Температура мен көміртегі мөлшерінің кремнийдің, алюминийдің тепе-теңдік дәрежесіне және осы металдардың қорытпадағы концентрациясына әсері анықталды. Кекстер қоспасын балқыту бойынша тәжірибелер Тамма пешінде изотермиялық режимде жүргізілді. Алынған нәтижелерге сүйене отырып, мыс кендерін көміртегімен және темірмен үймелі шаймалау кектерінің қоспасының тепе-теңдік әрекеттесуі FeSi, $FeSi_2$, $FeSi_{2.33}$, Fe_5Si_3, $FeSi_{2.43}$, Fe_3Si, Si, SiO_2, Al, SiC, $CaSiO_3$, Al_2SiO_5, $MgSiO_3$, K_2SiO_3, Na_2SiO_3, Cu, CO түзілуімен жүзеге асырылады. Темірдің шаймалау кек қоспасының массасынан 30-дан 50%-ға дейін және температураның 1600-ден 2000ºC-қа дейін ұлғаюы кремний қорытпасына экстракция дәрежесін 83.2%-ға дейін арттырады және ондағы кремний концентрациясын 40-41.41%-дан (1800ºC кезінде) 30-31%-ға дейін, алюминийді 2100ºC кезінде 8.3%-дан 5.5%-ға дейін төмендетеді. $FeSi_{45}$ маркалы ферросиллиций оған 74-81.9% Si алынып, 1780-1910ºC, 30% темір және 34% көміртек, ал $FeSi_{25}$ маркасы оған 70-76% Si алынып, 1660-1730ºC температуралық аймақта 43.5-50% темірдің қатысуымен түзіледі. Жоғары (≥80%) кремнийге жету үшін қорытпа кем дегенде 1800ºC температураны және процестің 80 минуттық ұзақтығын қажет етеді.

Негізгі сөздер: *тотыққан мыс кендері, шаймалау кектері, термодинамикалық модельдеу, айналмалы жоспарлау, электр балқыту, ферросилиций.*

Компьютерное термодинамическое моделирование и экспериментальное получение ферросплавов из смеси кеков выщелачивания окисленных медных руд

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Аннотация. В статье приводится результаты исследований компьютерного термодинамического моделирования и экспериментов по получению ферросплавов из смеси кеков сернокислотного выщелачивания окисленных медных руд месторождений Алмалы, Аяк-Коджан, Актогай, Коунрад, Шатырколь, содержащей (%): 65.2SiO_2; 14.2Al_2O_3; 7.4Fe_2O_3; 2.4K_2O; 2.7Na_2O; 6.6CaO; 2.8MgO; 0.2CuO. Моделирование проводились с использованием программного комплекса HSC-6.0, основанного на принципе минимума энергии Гиббса,а также метода планирования исследований с использованием рототабельного плана второго порядка (план Бокса-Хантера). Определялось влияние температуры и количества углерода на равновесную степень распределения кремния, алюминия и концентрацию этих металлов в сплаве. Эксперименты по плавке смеси кеков проводили на печи Тамма в изотермическом режиме. На основании полученных результатов установлено, что по равновесное взаимодействие смеси кеков кучного выщелачивания медных руд с углеродом и железом происходит с образованием FeSi, $FeSi_2$, $FeSi_{2.33}$, Fe_5Si_3,$FeSi_{2.43}$, Fe_3Si, Si, SiO_2,Al, SiC, $CaSiO_3$, Al_2SiO_5, $MgSiO_3$, K_2SiO_3, Na_2SiO_3,Cu, CO. Увеличение железа от 30 до 50% от массы смеси кеков выщелачивания и температуры от 1600 до 2000ºC повышает степенью извлечения в сплав кремния до 83.2%, и уменьшает концентрацию кремния в нем от 40-41.41% (при 1800ºC) до 30-31%, алюминия при 2100ºC от 8.3% до 5.5%. Ферросиллиций марки $FeSi_{45}$ с извлечением в него 74-81.9% Si образуется при 1780-1910ºC, 30% железа и 34% углерода, а марки $FeSi_{25}$ с извлечением в него 70-76% образуется в температурной области 1660-1730ºC в присутствии 43.5-50% железа. Для достижения высокого (≥80%) кремния в сплав необходима температура не менее 1800ºC и 80-ти минутная продолжительность процесса.

Ключевые слова: *окисленные медные руды, кеки выщелачивания, термодинамическое моделирование, рототабельное планирование, электроплавка, ферросилиций.*

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