Obtaining of ferrosilicon from technogenic magnetite concentrate

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Abstract. The article presents the results of studies on the production of ferrosilicon from iron ore (magnetite) concentrate and quartzite. The studies were carried out by thermodynamic simulation using the HSC-5.1 software package, based on the principle of Gibbs minimum energy and electric smelting of the concentrate together with coke and quartzite in a single-electrode arc furnace. Based on the studies, it was found that, under equilibrium conditions, the interaction of magnetite concentrate with silicon oxide (IV) and carbon is accompanied by the formation of FeSi (> 1200 °C), Fe₃Si (> 1100 °C), FeSi₂ (> 500 °C), Zn (> 800 °C), Pb (> 1200 °C); the degree of silicon extraction into the ferroalloy depends on the ratio in the SiO₂ / Fe₃O₄ mixture, decreasing from 85.6 to 66.1 (for example, at 1700 °C) with an increase in the SiO₂ / Fe₃O₄ ratio from 0.42 to 1.25. When melting a mixture containing 70% concentrate, 11% quartzite, 19% coke, a ferroalloy containing 15-18% Si. The resulting ferroalloys are graded from FeSi15 to FeSi45.

Keywords: magnetite concentrate, quartzite, coke, thermodynamic modeling, electric melting, ferrosilicon.

Introduction

Upon receipt of ferrosilicon, an obligatory component of the charge is iron shavings, the amount of which varies from 780 kg when smelting 1 ton of FS25 ferrosilicon to 250 kg when smelting FS75 ferrosilicon [1]. Now iron shavings are scarce material, the cost of which is 210-220 dollars per 1 ton [2]. It is possible to reduce the dependence of the production of silicon ferroalloys on scarce steel chips if another iron-containing material is used in the technology. Research in this direction is carried out by several methods. Thus, proposals are known for replacing steel chips in the production of ferrosilicon with other types of iron-containing raw materials, such as ferruginous quartzite, scrap metal, iron ore, pellets of pyrite cinders, etc. [3-6, 15]. Processing plant wastes are important sources of various types of mineral raw materials [7]. For example, based on the fact that the tailings of the Balkhash ore dressing plant contain 17% Fe [8] at Iron Concentrate Company LLP [9] from the
flotation tailings of copper-containing Sayak and Shatyrkol ores of the Balkhash ore dressing plant, iron-containing concentrate is obtained - magnetite concentrate containing 58 - 64% Fe. This concentrate can be used as a substitute for steel chips [10].

From a thermodynamic point of view, the reaction

$$6\text{SiO}_2 + \text{Fe}_3\text{O}_4 + 16\text{C} = 3\text{FeSi}_2 + 16\text{CO} \quad (1)$$

more preferred than reaction

$$2\text{SiO}_2 + \text{Fe} + 4\text{C} = \text{FeSi}_2 + 4\text{CO} \quad (2)$$

since it starts at 1392 °C, and the second when 1617 °C (table 1).

The aim of the work was to determine the possibility of obtaining a silicon alloy from magnetite concentrate, with the simultaneous extraction of lead and zinc from it.

**Materials and methods**

**Table 1** Influence of temperature on $\Delta G$ (kJ / mol FeSi$_2$) *

| Reaction number | 1000  | 1100  | 1200  | 1300  | 1392  | 1400  | 1500  | 1600  | 1617  | 1700  | 1800  |
|----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 1              | 343,2 | 255,1 | 167,0 | 79,9  | 0,0   | -7,1  | -93,8 | -180,3| -119,4| -263  | -346,4|
| 2              | 406,1 | 339,5 | 273,2 | 207,2 | 147,0 | 141,4 | 75,0  | 10,9  | 0,0   | -53,4 | -116,8|

* - $\Delta G_0$ calculation was performed using the software package HSC-5.1 [11]

The studies were carried out by the method of thermodynamic modeling and electric melting of the charge in an arc laboratory electric furnace.

Thermodynamic modeling was carried out using the HSC-5.1 software package and using the Equilibrium Compositions option [11]. The calculation of the equilibrium state by the software package is based on the principle of minimum Gibbs energy. Determination of the equilibrium degree of distribution of elements between substances was carried out according to our algorithm [12]. The electric smelting of the charge was carried out in an electric arc furnace (Fig. 1).

Energy was supplied to the furnace from the TDZhF transformer through an upper graphite electrode 3 cm in diameter and a graphite bottom. Before melting, a graphite crucible with an inner diameter of 6 cm and a height of 12 cm was installed on a graphite hearth. Then, the crucible was heated by an arc for 15-20 minutes. During this period, the current strength was 300-350 A and voltage 30-40V.

**Figure 1** Single-electrode arc furnace
The constancy of the furnace power was supported by a territor controller and the position of the electrodes in the crucible. The mass of the melted charge was 600-800g. The half-mass of the charge was initially loaded into the preheated crucible. Smelted it for 5-7 minutes. Then the remaining charge was loaded and melted in the furnace in three steps. When melting, the current strength was 400-450 A and voltage 20-30V. After melting, the crucible cooled in the furnace for 6-7 hours. Then it was removed from the furnace and cooled on a ceramic stand for another 4-5 hours, crashed. The content of the broken crucible was poured into ferroalloy, slag. The concentration of silicon, aluminum, and iron in the alloy was determined by the atomic adsorption method on an AAS-1 device (Germany) using a JEOL JSM-6490LM scanning electron microscope (Japan). The degree of extraction of metals from the alloy, the silicon content in the alloy, the melting point (1178 °C), the presence of reduced iron forms a ferroalloy (FeSi, Fe3Si, Fe). A complete transition of iron completely goes into elemental. 2FeO·SiO2 into 2FeO·SiO, quartzite (97% SiO2, 0.7% CaO, 0.7% Al2O3, 0.8% Fe₂O₃, 0.3% MgO, 0.2% H₂O, 0.3% other). - quartzite (97% SiO₂, 0.7% CaO, 0.7% Al₂O₃, 0.8% Fe₂O₃, 0.3% MgO, 0.2% H₂O, 0.3% other).

Research results

Thermodynamic modeling was carried out with two compositions of mixtures (table 2). It follows from the figures that in the systems under consideration, the products of interaction are 2FeO * SiO₂ (from 500 to 1400 °C), CaSiO₃, Na₂SiO₃, K₂SiO₃ (from 500 to 1900 °C), FeSi (from 1200 to 1900 °C), Fe₃Si (from 1100 to 1900 °C), Fe₂Si (from 1500 to 1900 °C), SiO₂ (from 1400 to 1900 °C), Fe (from 500 to 1900 °C), SiC (from 1500 to 1900 °C), Zn (from 800 to 1900 °C), Pb (from 1200 to 1900 °C).

Figures 2 and 3 show that at relatively low temperatures (500 - 760 °C), iron from Fe₃O₄ goes into 2FeO·SiO₂, and then (from 900 to 1300 °C) the iron completely goes into elemental. 2FeO·SiO₂ - fayalite in the system exists up to 900 °C, i.e. to its melting point (1178 °C) [1]. At temperatures above 1300 °C, silicon begins to recover, which in the presence of reduced iron forms a ferroalloy containing FeSi, Fe₃Si, Fe. A complete transition of silicon to the alloy from the first system does not occur due to the formation of more than 1600 °C gaseous SiO₂.

Table 2 The composition of the mixtures

| № Mixtures | The content in the mixture, kg | γ* |
|------------|-------------------------------|----|
|            | Fe₂O₃ | SiO₂ | CaO | Al₂O₃ | MgO | Na₂O | K₂O | PbO | ZnO | C |
| 1          | 85,9  | 107,1| 1,8 | 1,2  | 0,3 | 0,3  | 0,2 | 0,4 | 0,2 | 61 |
| 2          | 85,9  | 35,6 | 1,8 | 1,2  | 0,3 | 0,3  | 0,2 | 0,4 | 0,2 | 34 |

* γ* - mass ratio SiO₂/Fe₃O₄

Figure 2 Effect of temperature on the quantitative distribution of silicon (I) and iron (II) in system № 1
Figure 3 shows the effect of temperature on the equilibrium total degree of distribution of silicon in the alloy in the form FeSi₂, FeSi, Fe₃Si and SiC (α_Si_alloy). It is seen that from the first mixture (at γ = 1.25) α_Si_alloy is less than from the second (at γ = 0.42). This is due to the fact that when the first mixture is heated, a significant transition of silicon to gaseous SiO₂ is observed (at 1700 °C-16.2%, and at 1900 °C -31.8%), while from the second system the degree of transition of silicon to SiO₂ is, respectively 4.2% and 6.1%. From figure 6 it follows that the ferroalloy formed during heating of the first mixture contains more silicon than when heating the second. In accordance with [14], the conditions for the formation of vintage ferrosilicon can be determined from Figure 6. Vintage ferrosilicon from magnetite concentrate can be obtained in the almf region. So, in the acdb region (at 1400-1500 °C) ferrosilicon of the FeSi10 brand is formed, and the cefd region (at 1470-1900 °C) - of the FeSi15 brand, and in the ebfm region (at 1510-1900 °C) the FeSi25 brand. The extraction of zinc and lead in the gas phase is shown in table 3.

Figure 5 Effect of temperature and mixture composition on the equilibrium degree of silicon distribution
It can be seen that regardless of the composition of the initial mixtures $\alpha_{Zn}^g > \alpha_{Pb}^g$. Moreover, the complete distillation of zinc occurs at a temperature of more 1500 °C. High (≥70%) distillation is observed at a temperature of more 1700 °C.

Before electrofusion, the magnetite concentrate was poured together with bentonite clay and liquid glass, then granules (4-7 mm) were dried at 120 °C coke and quartzite were used with a 3-5 mm fraction.

![Figure 6](image)

**Figure 6** Effect of temperature and composition of the mixture on the concentration of silicon in the alloy

| № mixture | Metal | Temperature, °C |
|-----------|-------|-----------------|
|           |       | 1100  | 1200  | 1300  | 1400  | 1500  | 1600  | 1700  | 1800  | 1900  |
| 1         | Zn    | 75,6  | 86,2  | 92,5  | 96,2  | 98,8  | 99,4  | 99,9  | 99,9  | 99,9  |
|           | Pb    | 0,4   | 1,2   | 3,1   | 8,1   | 23,7  | 46,7  | 62,2  | 73,9  | 82,8  |
| 2         | Zn    | 61,4  | 76,2  | 85,6  | 92,5  | 97,5  | 99,4  | 99,9  | 99,9  | 99,9  |
|           | Pb    | 0,2   | 0,6   | 1,6   | 4,1   | 14,2  | 38,4  | 70,8  | 82,5  | 88,9  |

| № charge | Content, % | The predicted Si content in the alloy, % |
|-----------|-------------|-----------------------------------------|
|           | Concentrate | Quartzite | Coke               |
| 1         | 37,5        | 37,5      | 25,0               | 45                  |
| 2         | 59,0        | 22,0      | 21,0               | 25                  |
| 3         | 70,0        | 11,0      | 19,00              | 15                  |

Using the pycnometric method (according to the density of the ferroalloy), it was found that the silicon content in the ferroalloy obtained from the first charge was 29-41%, from the second 21-26%, for the third - 15-18%. In accordance with [13] obtained ferroalloys corresponds to ferrosilicon grades FeSi15 and FeSi45. Figure 7 shows a photograph of the alloy, and Figure 8 shows the results of electron microscopic analysis of the surface of ferroalloys.

![Figure 7](image)

**Figure 7** Photograph of a sample of ferroalloy, obtained from the mixture of the first composition
Conclusions

Based on the results of obtaining ferroalloy from magnetite concentrate, the following conclusions can be drawn:

- under equilibrium conditions, the interaction of a magnetite concentrate with silicon oxide (IV) and carbon is accompanied by the formation of FeSi (> 1200 °C), Fe₂Si (> 1100 °C), FeSi₂ (> 500 °C), Zn₉ (> 800 °C), Pb₉ (> 1200 °C); the degree of extraction of silicon in the ferroalloy depends on the ratio in the mixture SiO₂/Fe₃O₄ decreasing from 85.6 to 66.1 at 1700 °C with increasing ratio SiO₂/Fe₃O₄ from 0.42 to 1.25;
- formation 2FeO·SiO₂ from Fe₃O₄ occurs in the temperature range 500 – 900 °C, that is, to the melting point of fayalite (1178 °C), therefore, the formation of ferrosilicon comes from the system SiO₂ – Fe – C; during electrosmelting of a mixture consisting of 37.5% concentrate, 37.5% quartzite, 25% coke, a ferroalloy containing 29-41% silicon is formed, and when melting a mixture containing 70% concentrate, 11% quartzite, 19% coke, a ferroalloy containing 15-18% Si; the resulting ferroalloys have a brands from FeSi₁₅ до FeSi₄₅.

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Получение ферросилиция из техногенного магнетитового концентрата

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Аннотация. В статье приводятся результаты исследований по получению ферросилиция из железорудного (магнетитового) концентрата и кварцита. Исследования проводили методом термодинамического моделирования с использованием программного комплекса HSC-5.1, основанного на принципе минимума энергии Гиббса и электроплавкой концентрата совместно с коксом и кварцитом в дуговой одноэлектродной печи. На основании проведенных исследований установлено, что, в равновесных условиях взаимодействие кварцита, кокса, термодинамического моделирования, электролиза и электроплавки, получение ферросилиция возможно при использовании железорудных неофлюсованных окатышей.

Ключевые слова: магнетитовый концентрят, кварцит, кокс, термодинамика, модель ЕВМ, метталлург и металлургия

Литература

[1] Гасик М.И., Ляншиев М.П., Емлин Б.И. Теория и технология производства ферросплавов. -М.: Металлургия, 1988. - 784 с.
[2] Стальная стружка цена. Информационное агентство MetalTorg.Ru. Новости, аналитика, цены, статистика рынка черных, цветных и драгоценных металлов. [Электронный ресурс] URL: https://www.metaltorg.ru/stalnaya-struzhka-tsen.html (дата обращения: 15.03.2020).
[3] Теслев С. А., Теслева Е. П. Использование железорудных неофлюсованных окатышей при производстве ферросилиция // Инновационные технологии и экономика в машиностроении: сб. трудов VI Международной научно-практической конференции, Юрга, 21-23 Мая 2015. - Томск: ТПУ, 2015. - С. 155-158
[4] Патент РФ № 2 704 872. Шихта для изготовления ферросилиция / Лоханкин А.П., Либенсон Б.Н., Касаткин Д.А. Опубл. 31.10.2019. Бюл. №31
[5] Соловян А. В. Способ замены стружки при выплавке ферросилиция // Неразрушающий контроль: сборник научных трудов № 4. – М.: Изд-во МИТТ, 2015. - С. 141-144.
[6] Патент РФ № 2109836 Шихта для получения ферросилиция / Зайко В.П., Садитдинов В.А., Петров А.А., Карнаухов В.Н., Воронов Ю.И., Лапченков В.И., Исхаков Ф.М. Опубл. 27.04.1998.
[7] Леонтьев Л. И., Шешуков О. Ю., Некрасов И. В. Анализ, переработка и использование техногенных отходов металлургического производства // Комплексное использование минерального сырья. № 4. 2014. с.8-25.
[8] Шевко В.М., Айтулов Д.К., Сержанов Г.М., Каратаева Г.Е., Бадикова А.Д. Комплексная переработка хвостов обогащения медь-содержащих руд // Шымкент: ЮКГУ. - 2019. – 203 с.
[9] Продукция Iron Concentrate Company, Iron Concentrate Company [Электронный ресурс]. URL: http://iccker.com/ru/node/39 (дата обращения: 15.03.2020).
[10] Шевко В.М., Бадикова А.Д., Тулеев М.А., Аманов Д.Д., Капсалимов С.А. Термодинамическое обоснование и технология получения ферросплава, карбюра кальция из доменного шлака с заменой стальной стружки на магнетитовый концентрят // Международный журнал прикладных и фундаментальных исследований. – 2020. – № 4. – С. 83-90
[11] Antti Roine, Jarkko-Mansikka-aho, Tuukka Kotiranta, Peter Bjorklund, Pertti Lamberg. HSC Chemistry 6.0 User's Guide. Outotec Research Oy. August 14, 2006
[12] Свидетельство на объект, охраняемый авторским правом РК №1501 от 29 января 2019г. Расчет равновесного распределения элементов применительно к программному комплексу HSC-5.1. Программа для ЭВМ. / Шевко В.М., Сержанов Г.М., Каратаева Г.Е., Аманов Д.Д.
References

[1] Gasik M.I., Lyakishev M.P., Emlin B.I. Teoriya i tekhnologiya proizvodstva ferrosplavov (Theory and technology for the production of ferroalloys). Moscow: Metallurgy. 1988, 784 (in Russ.).

[2] Steel shavings price. News Agency MetalTorg.Ru. News, analytics, prices, market statistics for ferrous, non-ferrous and precious metals. [Electronic resource] URL: https://www.metaltorg.ru/stalnaya-struzhka-teshta.htm (15.03.2020)

[3] Teslev S. A., Tesleva E. P. Ispol'zovaniye zhelezo rudnykh neoflyusovannikh okatyshey pri proizvodstve ferrosilita (The use of non-flushed iron ore pellets in the production of ferrosilicon) VI Mezhdunarodnaya nauchno-prakticheskaya konferentsiya studentov, aspirantov i molodyh uchenykh (Non-destructive testing: electronic instrumentation, technology, safety: a collection of labor resources of the All-Russian Scientific and Practical Conference on students, graduate students and young scientists) Tomsk, Russia, 2015. 155-158 (in Russ.).

[4] Pat. 2 704 836 RU. Shikhta dlya izgotovleniya ferrosilita (The mixture for the manufacture of ferrosilicon)/ Lokhankin A.P., Libenson B., Kasatkin D.A. Opubl. 31.10.2019, 31 (in Russ.).

[5] Solovyan A. V. Sposob zameny struzhki pri vypalke ferrosilita (A method for replacing chips in the smelting of ferrosilicon) Nanrezhazhajushhij kontrol': jelektronnoe priborostroenie, tehnology, bezopasnost': shornik trudov V Vserossijskoy nauchno-prakticheskoj konferentsii studentov, aspirantov i molodyh uchujshykh (Non-destructive testing: electronic instrumentation, technology, safety: a collection of labor resources of the All-Russian Scientific and Practical Conference of students, graduate students and young scientists) Tomsk, May 25-29, 2015: in 2 volumes - Tomsk: TPU Publishing House, 2015. V. 2. P. 141-144. (In Russ)

[6] Pat 2 109 836 RU. Shihto dlya poluchenija ferrosilita (A charge for producing ferrosilicon)/ Zajko V.P., Saditdinov V.A., Petrov A.A., Karnauhov V.N., Voronov Ju.I., Lapchenkov V.I., Ishakov F.M. – opubl. 27.04.1998. (In Russ)

[7] Leont'ev L. I., Sheshukov O. Ju., Nekrasov I. V. Analiz, pererabotka i ispol'zovanie tehnogennykh otyedov metallurgicheskogo proizvodstva (Analysis, processing and use of technogenic wastes of metallurgical production) Kompleksnoe ispol'zovanie mineral'nogo syr'ya (Complex use of mineral raw materials) - № 4. 2014. P.8-25.

[8] Shevko V.M., Aitkulov D.K., Serzhanov G.M., Karataeva G.E., Baidikova A.D. Kompleksnaja pererabotka hvostov obogashchennyh med'soderzhashhikh rud = Complex processing of copper ore dressing tailings. Shymkent: SKSU. - 2019. - 203 p. (in Russ)

[9] Products of Iron Concentrate Company // Iron Concentrate Company [Electronic resource]. URL: http://icckaz.com/ru/node/39 (accessed: 03.15.2020).

[10] Shevko V.M., Baidikova A.D., Tuleev M.A., Amanov D.D., Kapsaljamov S.A. Termidonimicheskoe obosnovenie i tekhnologija poluchenija ferrosillava, karnbida kal'cija iz domennogo shlaka s zamenoj stal'noj struzhki na magnetitovyj koncentrat (Thermodynamic rationale and technology for producing ferroalloy, calcium carbide from blast furnace slag with the replacement of steel chips with magnetite concentrate) Mezhdunarodnyj zhurnal priljadnyh i fundamental'nyh issledovanij = International Journal of Applied and Basic Research, 2020. – № 4. - P. 83-90 (In Russ)

[11] Anti Roine, Jarkko-Mansikka-aho, Tuuuka Kotiranta, Peter Bjorklund, Perti Lamberg. HSC Chemistry 6.0 User's Guide. Outotec Research Oy. August 14, 2006

[12] Copyright Certificate 1501 Raschet ravnovesnogo rasprosdeniya jelementov primentel'nogo k programmnomu kompleksu HSC-5.1. Programma dlya JeVM. (Calculation of the equilibrium distribution of elements as applied to the HSC-5.1 software package. The program for the computer.) / Shevko V.M., Serzhanov G.M., Karataeva G.E., Amanov D.D. 29.01.2019

[13] Shevko V.M., Amanov D.D., Karateva G.E., Aitkulov D.K. Kinetika poluchenija kompleksnogo ferrosillava iz kremen'-adjuminisoderzhashhej opoki (Kinetics of obtaining a complex ferroalloy from a silicon-aluminum-containing silica clay) Mezhdunarodnyj zhurnal priljadnyh i fundamental'nyh issledovanij = International Journal of Applied and Basic Research. 2016. - № 10-2. - P. 194-196.

[14] State standard 1415-93 Ferrosilitije. Mezhgosudarstvennyj standart. (Ferrosilicon. Interstate Standard) Minsk: IPK. Publishing house of standards. 1997. -14p.

[15] Shevko V.M., Baidikova A.D., Tuleev M.A., Karataeva G.E. Kinetics of extraction of the silicon, aluminum and calcium of the basalt from the daubaba deposit // Kompleksnoe ispol'zovanie Mineral'nogo syr'ya / Complex Use of Mineral Resources / Mineral'nyj Shiksiattady Keshendi Paidalanu. 2019. 2. 83–89. https://doi.org/10.31643/2019/6445.20