THERMODYNAMIC SUBSTANTIATION OF PRODUCING SILICON-CONTAINING FERROALLOYS FROM PERLITE

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ABSTRACT

Perlite, which is quite widely used in various industries (construction, oil, chemical, food, agriculture and several other industries) due to the content of amorphous silica, which has increased reactivity, can become a reserve raw material for producing silicon-containing ferroalloys. The article presents the results of studies on the possibility of producing ferrosilicon and ferrosilicoaluminium from perlite in the presence of iron and carbon. The studies were carried out by thermodynamic modelling using the HSC-6.0 software package, as well as by methods of rotatable planning and geometric optimization. The conditions (temperature, amount of iron) have been determined that allow the extraction of 75 - 80 % of silicon into FeSi45 grade ferrosilicon (41.3 - 42.2 % of Si) and into FSA5510 grade ferrosilicoaluminium, containing 51.8 - 52.2 % of Si and 7.5 - 8.8 % of Al.

<u>*Keywords*</u>: *amorphous silicon - containing rock, perlite, silicon alloy, ferrosilicon, thermodynamic modelling.*

INTRODUCTION

The main silicon - containing raw material in the ferrosilicon technology is quartzite. Its consumption per 1 ton of ferrosilicon is from 370 (FeSi20) to 1930 kg (FeSi75) [1]. To improve the economic indicators of ferrosilicon production, it is necessary to search for effective types of silica - containing raw materials with increased reactivity. This category of raw materials includes amorphous silicon - containing rocks - opoka, diatomite, tripoli [2 - 8], as well as perlite containing 68 - 75 % of SiO_2, 11 - 14 % of Al_2O_3, 0.6 - 5 % of $\sum CaO$ and MgO, 3 - 11 % of $\sum Na_2O$ and K_2O, 2.4 - 3.8 % of $\sum Fe_2O_3$ and FeO, loss after ignition - 0.2 - 5 %, 3 - 8 % of bound water [9]. The world reserves of perlite are 700 million tons [10, 11]. Due to its good swelling properties, perlite is used in the construction industry (asbestos - perlite cement, silicate perlite, bitumen perlite, carboperlite, ceramic perlite, gypsum perlite, basalt - perlite fiber, etc.) [12 - 18], oil industry, cryogenic engineering, food and chemical industries

[19 - 22], horticulture, and also in metallurgy (production of refractory materials, melting cast iron and steel in a ladle) [23 - 25]. There are several known methods of using perlite for producing of sorbents for extracting oil, oil products and liquid hydrocarbons from aqueous media [26 - 29], as well as hydrophobic, reinforced, lightweight hydrospheres, used not only as a sorbent, but also as a lightweight reinforcing filler in the chemical industry [30, 31].

Results of the studies of the hydrothermal - alkaline method for producing dicalcium silicates with a modulus of 1:4 by extracting up to 60 % of SiO_2 from perlite rock are presented in [32]. Comprehensive processing of perlite, containing 71 - 74 % of SiO_2, provides the possibility of producing silicates of various metals, amorphous silica, calcined and caustic soda from it by an alkaline - acid combined method [33].

Considering the positive results of studies on the smelting of ferrosilicon from amorphous silica - containing rocks, the article presents the results of the research on the possibility of producing a silicon

ferroalloy from perlite in the presence of iron and carbon [34 - 36].

EXPERIMENTAL

The chemical composition of the perlite used in the research was the following, mass. %: 76.9 SiO_2(G), 13.0 Al_2O_3, 1.2 CaO, 1.0 Fe_2O_3, 3.6 K_2O, 0.7 MgO, 4.1 Na_2O, 0.5 TiO_2. (The designation (G) for SiO_2 corresponds to the amorphous form of quartzite in the HSC database.)

The studies were carried out by thermodynamic modelling using the HSC - 6.0 software package based on the principle of minimum Gibbs energy, the temperature range is 500 - 2000ºC, the pressure is 1 bar [37]. The amount of iron was varied from 18 to 42 %

of the perlite mass (18 % iron by weight of pearlite was selected to produce FeSi65 grade ferrosilicon and 42 % was selected to produce FeSi50 grade). The amount of carbon was constant in accordance with the stoichiometry for the reduction of SiO_2, Al_2O_3 and Fe_2O_3. Some studies were implemented using the second - order rotatable design (Box - Hunter plan) [38].

RESULTS AND DISCUSSION

Fig. 1 shows the effect of temperature and iron on the equilibrium degree of silicon distribution in the products of perlite reduction with carbon.

It is evident that the main SiO_2 reduction products (which occurs at a temperature of > 1200ºC) are FeSi,
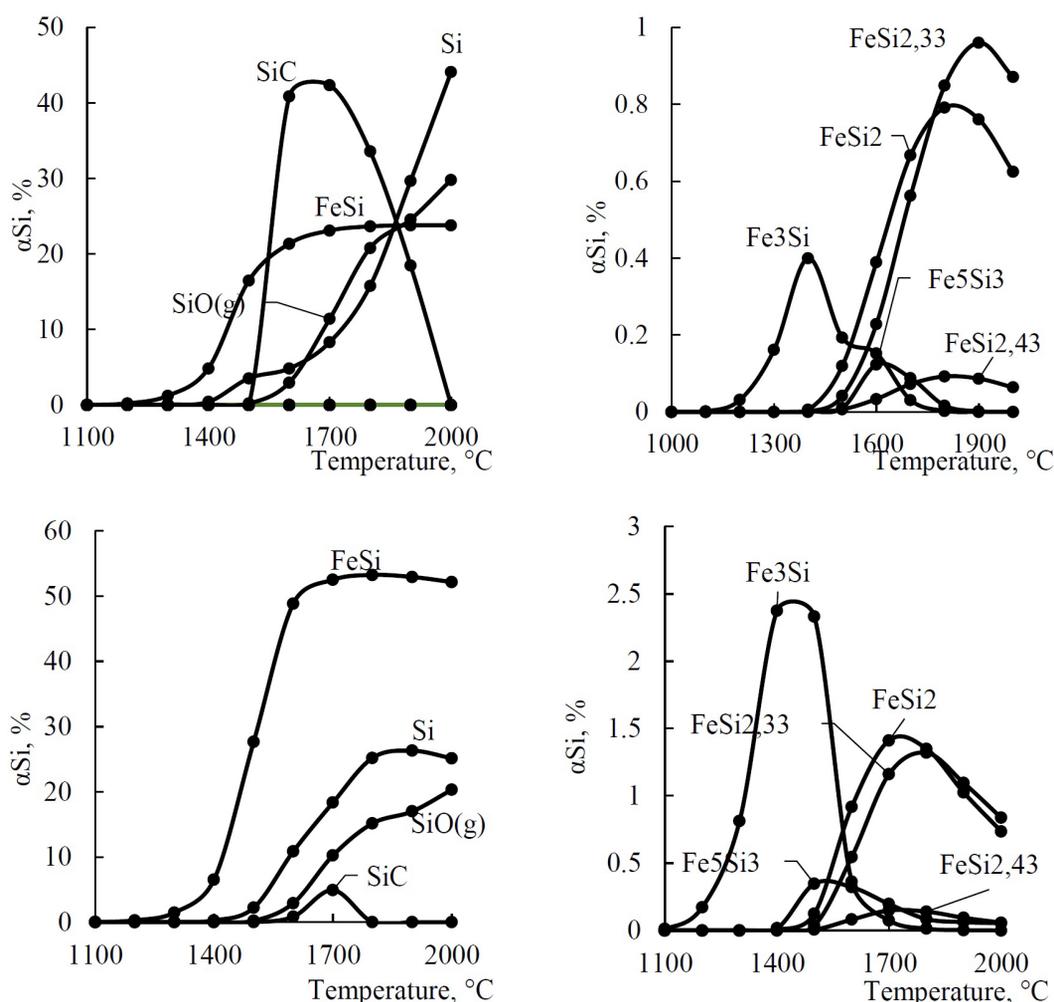
Amount of iron, %: I - 18, II - 42.
Fig. 1. The effect of temperature and iron on the equilibrium degree of silicon distribution into the products of perlite reduction with carbon.

SiO(g), Si and SiC (to a lesser extent, silicon also turns into Fe_3Si, Fe_5Si_3, $FeSi_2$, $FeSi_{2.33}$ and $FeSi_{2.43}$). An increase in the amount of iron leads to a significant change in the equilibrium degree of silicon extraction into the SiO_2 reduction products (Fig. 2). Thus, an increase in the amount of iron increases the degree of silicon conversion into all silicides, up to 1880ºC - silicon into its elemental state, as well as the total silicon extraction into the resulting alloy to 81.3 % at 1800ºC and reduces the silicon extraction into SiC and SiO (g) (for example, at 1800ºC from 33.6 to 0 % and from 20.8 to 15.2 %, respectively).

A decrease in the degree of silicon extraction into SiC with an increase in the amount of iron is associated with its ability to destroy silicon carbide [39, 40]. For instance, ΔG^0 of the reaction presented in the Eq. (1):

$$SiC + Fe = FeSi + C \qquad (1)$$

calculated using the reaction equations module of the HSC - 6.0 software package is - 14.9 kJ at 1500ºC, and - 25.8 kJ in 1800ºC.

The decrease in the transition of silicon into SiO is explained by the fact that the carbon formed in reaction (1) reacts with SiO(g) according to the reaction presented in the Eq. (2):

$$SiO(g) + C = Si + CO \qquad (2)$$

ΔG^0 of this reaction is - 22.3 kJ at 1500ºC, and - 33.5 kJ in 1800ºC.

It should be noted that aluminium in the system begins to be reduced at a temperature above 1700ºC. With an increase in the amount of iron in the charge, the degree of aluminium reduction decreases from 68.8 to 53.1 at 2000ºC. At the same time, from 7.1 to 5.1 % of aluminium passes into gas.

The effect of iron on the concentration of silicon and aluminium in the alloy is shown in Fig. 3.

Increasing the iron content in the charge leads to decreasing in the silicon and aluminium concentrations in the alloy. For example, the silicon concentration at 1800 - 1900ºC reduces from 44.0 - 50.3 % to 40.5 - 40.0 %, and the aluminium concentration in the alloy at 1900 - 2000ºC decreases from 2.2 - 8.9 % to 1.5 - 4.5 %. The phase composition of the resulting ferroalloy is given in Table 1.

It is evident that the main silicon - containing phases are FeSi and Si. At a small amount of iron, an increase in the temperature reduces the concentration of the FeSi phase due to an increase in the silicon and aluminium concentrations. At 42 % of iron, the concentration of FeSi decreases less noticeably due to a less significant increase in the aluminium concentration in the alloy.

To determine the optimal conditions for the possible production of high - quality ferrosilicon from pearlite, further studies were carried out using the second order rotatable design. Independent factors in the study are temperature, ºC (T, ºC) and the amount of iron, % (Fe, %). Optimization parameters are the degree of silicon extraction into the alloy (αSi(alloy), %) and the silicon concentration in the alloy (CSi(alloy), %). The research planning matrix and the results are presented in Table 2.

Using the results of the study adequate regression equations of αSi(alloy) = f(T, Fe) and CSi(alloy) = = f(T, Fe) was obtained [41]. Then, in accordance with [42], volumetric and planar images of the change in αSi(alloy) and CSi(alloy) depending on the temperature and amount of iron were constructed.

The obtained regression equations (Eq. (3) and Eq. (4)) have the form:

$$\alpha Si_{(alloy)} = -762.62 + 0.738T + 4.852Fe - 1.664 \cdot 10^{-4}T^2 + 8.456 \cdot 10^{-3}Fe^2 - 2.195 \cdot 10^{-3}T\,Fe \qquad (3)$$

$$CSi_{(alloy)} = -299.08 - 0.33T - 1.652Fe - 7.41 \cdot 10^{-5}T^2 + 7.97 \cdot 10^{-3}Fe^2 - 1.284 \cdot 10^{-3}T\,Fe \qquad (4)$$

The obtained equations are adequate to the research, since for the selected level of reliability (≥ 95 %) [38], the tabular value of the Fisher criterion (6.59) is greater than the calculated values of the criterion: 6.583 for Eq. (3) and 1.059 for Eq. (4).

The constructed images (volumetric and horizontal) are shown in Fig. 4.

Judging by the figure, the maximum αSi(alloy) (82.2 %) occurs in 1900ºC in the presence of 42 % of iron, and the maximum silicon concentration in the alloy (48.7 %) is achieved in 1900ºC in the presence of 18 % of iron. The FeSi45 grade of ferrosilicon (41 - 47 % of Si) [43] is formed in the shaded area of the figure, and the FeSi50 grade of ferrosilicon (47 - 48.7 % of Si) - in the *xyz* region.

To determine the conditions for the formation of high
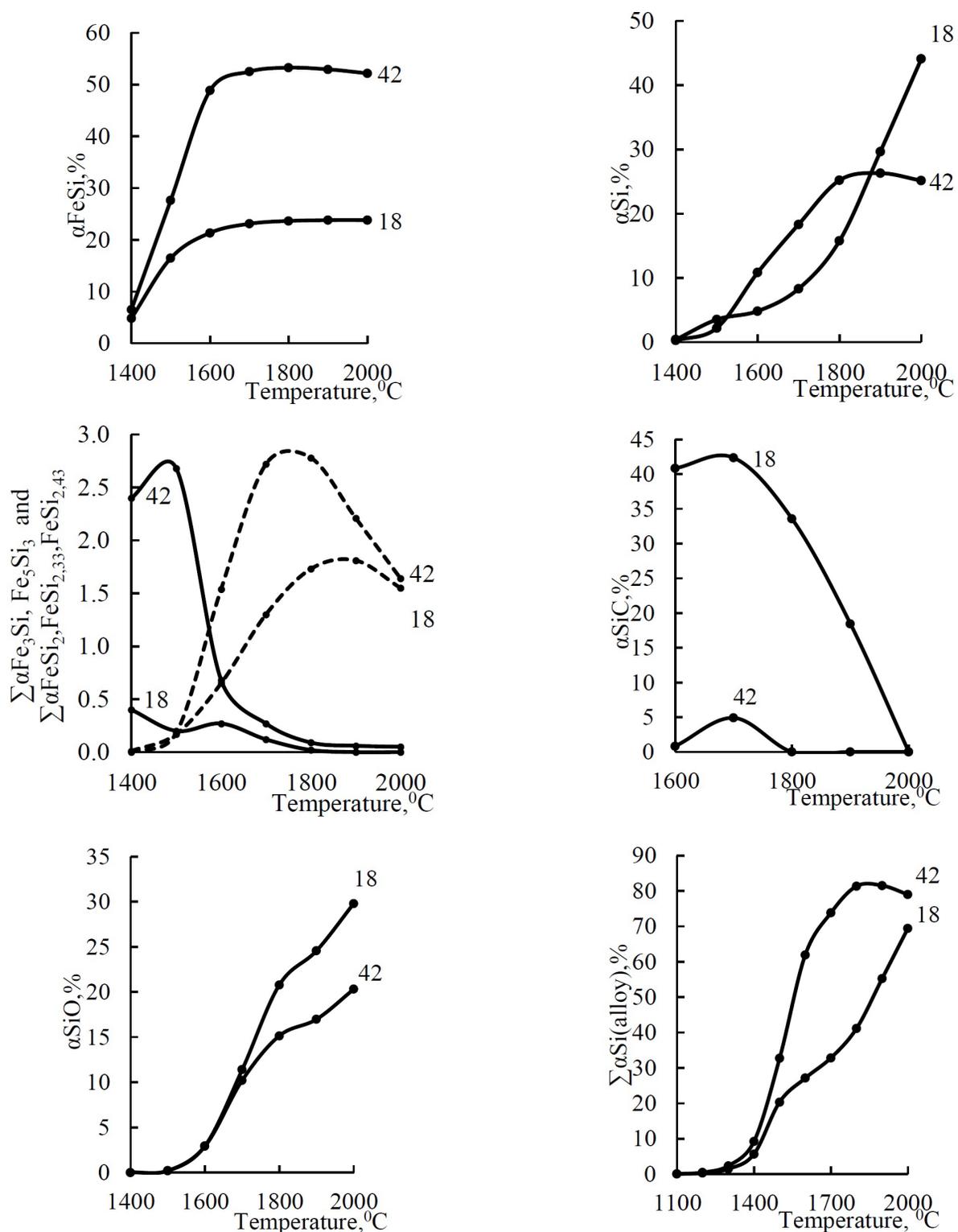
The numbers near the lines - the amount of iron, % of the perlite mass.

The degree of silicon distribution into: I - FeSi, II - Si, III (—) - $\alpha Si \sum FeSi_2$, $FeSi_{2.33}$, $FeSi_{2.43}$;

(- -) - $\sum Fe_3Si$, Fe_5Si_3; IV - SiC, V - SiO(g), VI - Si(alloy).

Fig. 2. The effect of temperature and iron on the degree of silicon distribution into the products of perlite reduction with carbon.
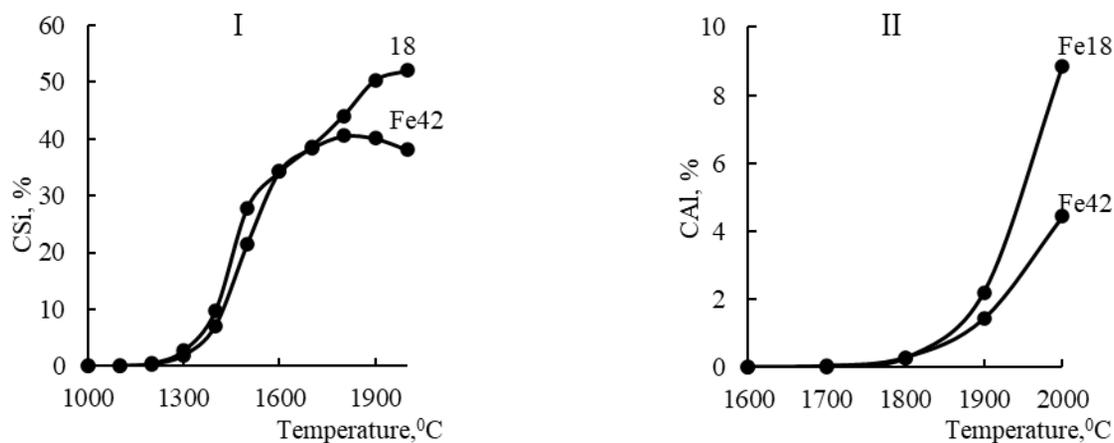
The numbers near the lines - the amount of iron, % of the pearlite mass.
Fig. 3. The effect of temperature and iron on the concentration of silicon (I) and aluminium (II) in the alloy.
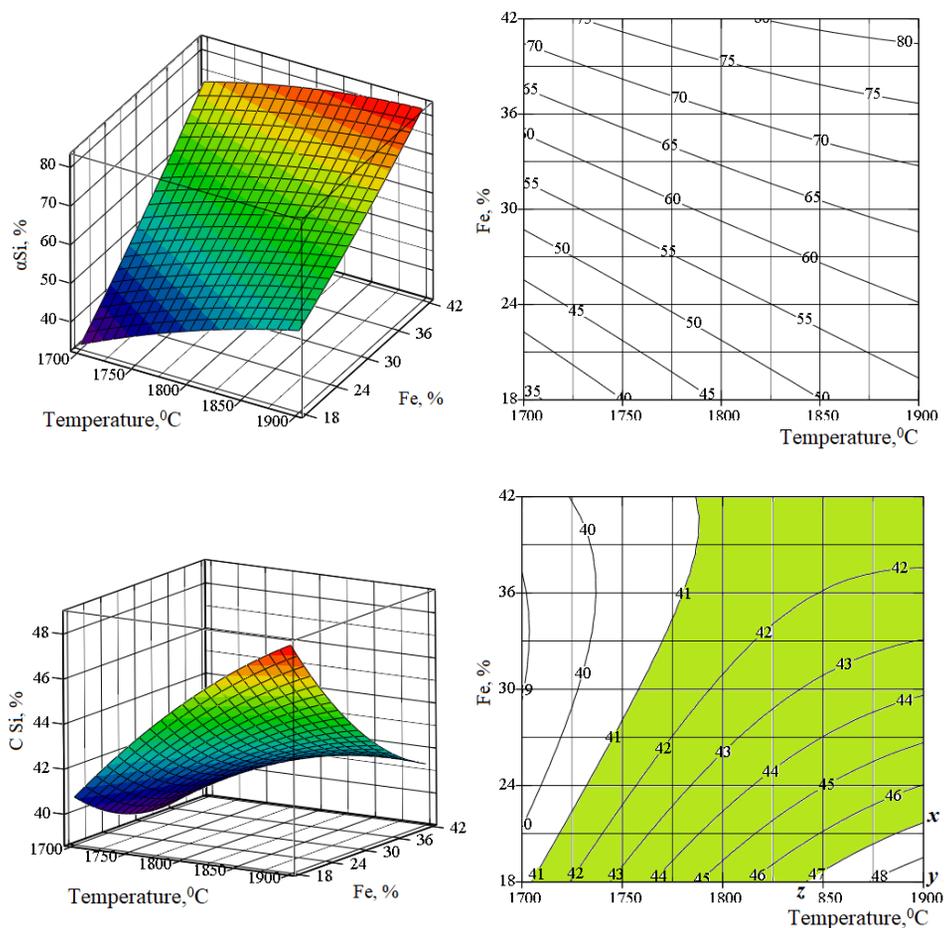
Images: A - volumetric, B - planar.
Fig. 4. The effect of temperature and amount of iron on the degree of silicon extraction in the alloy (I) and the silicon concentration in the alloy (II).

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Table 1. Phase composition of the alloy.

Fe, %	T,°C	Fe	Si	FeSi	Fe$_3$Si	Fe$_5$Si$_3$	FeSi$_2$	FeSi$_{2.33}$	FeSi$_{2.43}$	Al	Others*
18	1800	3.04	16.86	75.56	0.02	0.08	1.68	1.67	0.17	0.27	0.65
	2000	2.46	33.05	53.32	< 0.01	< 0.01	0.93	1.21	0.09	8.86	0.06
42	1800	4.95	12.53	79.22	0.05	0.18	1.34	1.21	0.13	0.29	0.1
	2000	6.46	12.14	75.29	< 0.01	0.11	0.71	0.75	0.05	4.44	0.04
*) $\sum$Na, K, Mg, Ca											

Table 2. The matrix and the research results.

#	Variables				Parameters			
	Coded		Natural					
	X1	X1	T, °C	Fe, %	$\alpha Si_{(alloy)}$, % research	$\alpha Si_{(alloy)}$, % according to the equation	$C_{Si(alloy)}$, % research	$C_{Si(alloy)}$, % according to the equation
1	- 1	- 1	1871	38.5	42.5	42.3	41.5	41.4
2	+ 1	- 1	1729	38.5	56.0	55.4	47.0	46.4
3	- 1	+ 1	1871	21.5	67.0	68.9	39.8	39.9
4	+ 1	+ 1	1729	21.5	75.2	76.6	42.2	41.8
5	+ 1.414	0	1900	30	67.0	66.7	43.3	43.9
6	- 1.414	0	1700	30	53.0	52.0	39.0	38.9
7	0	+ 1.414	1800	42	81.3	79.2	41.0	41.1
8	0	- 1.414	1800	18	44.5	45.3	45.1	45.5
9	0	0	1800	30	62.0	61.0	42.0	42.2
10	0	0	1800	30	61.6	61.0	42.7	42.2
11	0	0	1800	30	61.0	61.0	42.8	42.2
12	0	0	1800	30	60.6	61.0	41.8	42.2
13	0	0	1800	30	60.0	61.0	41.5	42.2

- quality ferrosilicon, a combined image of $\alpha Si_{(alloy)}$, $CSi_{(alloy)} = f(T, Fe)$ was constructed (Fig. 5). In this case, to determine the optimal temperature and amount of iron for formation of FeSi45, the following conditions were adopted: $\alpha Si_{(alloy)} \geq 75$ %, $CSi_{(alloy)} = 41 - 47$ %, and for FeSi50 - $CSi_{(alloy)} \geq 47$ %.

From Fig. 5 it is evident that, based on the accepted conditions, FeSi45 ferrosilicon is formed in the abcd region, and FeSi50 in the xyz region. The process parameters at the boundary points of the abcd and xyz regions are presented in Table 3.

According to Technical Specifications 0820-011-14513884-2013, a ferrosilicoaluminium alloy must contain at least 7.5 % of aluminium [44]. From Fig.

3 this condition is met at 2000°C and 18 % of iron. From Fig. 6 it follows that at 18 % of iron, a ferroalloy with aluminium concentration of ≥ 7.5 % is formed in the temperature interval of 1985 - 2000°C. The $CSi_{(alloy)}$ in this temperature range is 51.8 - 52.1 % (Fig. 6). In terms of aluminium (7.5 - 8.8 %) and silicon (51.8 - 52 %) content, the resulting alloy is close to ferrosilicoaluminium of FS55A10 grade [44].

For the practical implementation of the technology for producing silicon - containing ferroalloys from perlite, a preliminary processing is necessary, which involves its swelling. This can be a slow heat treatment with the release of crystallization moisture to the softening temperature of perlite (i.e. $\approx$ up to 850 - 1200°C) [45, 46].
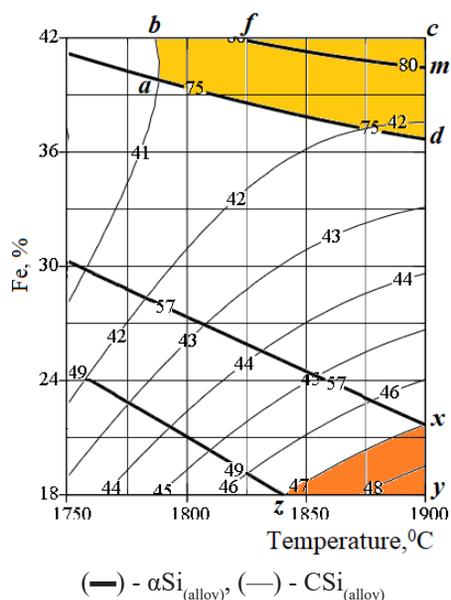
(—) - αSi$_{(alloy)}$, (—) - CSi$_{(alloy)}$

Fig. 5. Combined image of the temperature and iron effect on αSi(alloy) and CSi(alloy).

Table 3. Values of the process parameters at the boundary points of the FeSi45 and FeSi50 ferrosilicon formation areas.

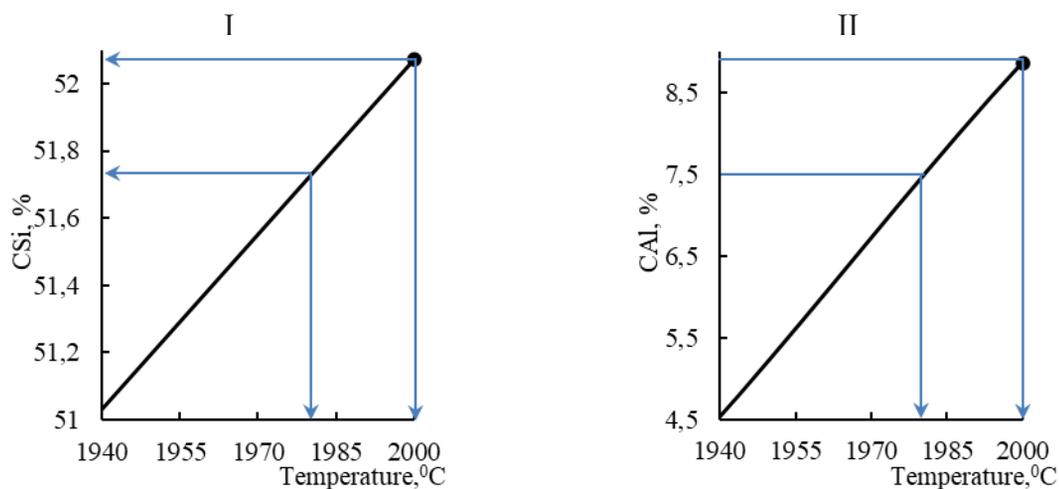| Point in Fig. 5	T, ⁰C	Fe, %	αSi$_{(alloy)}$, %	C$_{Si(alloy)}$, %	The alloy grade
a	1876	39.8	75.0	41.6	
b	1873	42.0	78.4	41.4	FeSi45
c	1900	42.0	82.2	41.3	
d	1900	36.7	75.0	42.2	
x	1900	22.3	57.0	46.7	
y	1900	18.0	53.4	48.7	FeSi50
z	1841	18.0	49.0	47.0	
f	1825	42.0	80.0	41.3	FeSi45
m	1900	40.8	80.0	41.5	

Fig. 6. The effect of temperature on the aluminium (I) and silicon (II) concentrations in the alloy in the temperature range of 1950 - 2000⁰C at 18 % of iron.

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CONCLUSIONS

Based on the obtained results on the equilibrium interaction of perlite with carbon and iron, the following conclusions can be made:

- products of SiO_2 reduction at the temperature of > 1200ºC are Fe_3Si, $FeSi$, Fe_5Si_3, $FeSi_2$, $FeSi_{2.33}$, $FeSi_{2.43}$, $SiO(g)$, Si and SiC;
- an increase in the amount of iron increases the degree of silicon transition into the alloy in the form of iron silicides and elemental silicon and reduces losses in the form of SiC and SiO(g);
- ferrosilicon of FeSi45 grade with a content of 41.3 - 42.2 % of Si (the extraction of silicon into the alloy is 75 - 80 %) can be produced in the presence of 36.7 - 42 % of steel shavings in the temperature range of 1825 - 1900ºC;
- the formation of ferrosilicoaluminium of FS55A10 grade containing 51.8 - 52 % of Fe and 7.5 - 8.8 % of Al and with the silicon extraction degree of 80 % takes place in the temperature interval of 1985 - 2000ºC in the presence of 18.0 - 22.3 % of iron.

Authors' contributions

V.Sh.: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision.

REFERENCES

1. N.P. Lyakishev, M.I. Gasik, V.Y.A. Dashevskiy, Metallurgy of ferroalloys part 1. Metallurgy of silicon, manganese and chromium, Moscow, MISiS, 2006, (in Russian).
2. S. Kurilova, A. Naumov, B. Gebru, Silica clay (opoka) as a promising raw material for unfired wall products by compression molding, E3S Web Conf., 419, 2023, 01030. https://doi.org/10.1051/e3sconf/202341901030
3. S.G. Borisade, S.S. Owoeye, A. Ayeni, Synthesis and characterization of pure amorphous silicon oxide from treated kaolinitic clay using chemical extraction, J. Chem. Technol. Metall. , 59, 3, 2024, 613-622. https://doi.org/10.59957/jctm.v59.i3.2024.15
4. O.A. Dobrinskaya, N.I. Min'ko, Reactivity of Amorphous Rocks from the Point of View of Their Interaction in Charges for Glass-Crystalline Materials, Glass Physics and Chemistry, 48, 5, 2022, 422-428. https://doi.org/10.1134/S1087659622800021
5. A.A. Reka, B. Pavlovski, B. Boev, S. Bogoevski, B. Boškovski, M. Lazarova, A. Lamamra, A. Jashari, G. Jovanovski, P. Makreski, Diatomite - evaluation of physico-mechanical, chemical, mineralogical and thermal properties Geologica Macedonica, 35, 1, 2021, 5-14. https://doi.org/10.46763/GEOL21351368005ar
6. V. Erofeev, A. Rodin, V. Bochkin, A. Ermakov, The formation mechanism of the porous structure of glass ceramics from siliceous rock, Magazine of Civil Engineering, 100, 8, 2020, art. no. A6. https://doi.org/10.18720/MCE.100.6
7. N.M Mirkayev., V.M Shevko., D.K. Aitkulov, A.D. Badikova, Thermodynamic and experimental substantiation for obtaining ferrosilicon from tripoli, Metallurgical Research and Technology, 120, 1, 2023, art. no. 113. https://doi.org/10.1051/metal/2023003
8. A. Yoleva, S. Djambazov, S. Sabrieva, A. Gigova, Study on the Preparation of Ceramic Membranes Based on Natural and Waste Materials, J. Chem. Technol. Metall., 55, 2, 2020, 367-371.
9. A.B. Bajbatsha, The geology of mineral deposits: A textbook. Volume I. Almaty, New book, 2021, (in Russian).
10. S.G. Maxineasa, D.N. Isopescu, M.L. Lupu, I-R. Baciu, L. Pruna, C. Somacescu, The use of perlite in civil engineering applications, IOP Conference Series: Materials Science and Engineering, 1242, 2022, 012022. https://doi.org/10.1088/1757-899X/1242/1/012022
11. A.G. Celik, A.M. Kilic, G.O. Cakal, Expanded perlite aggregate characterization for use as a lightweight construction raw material Physicochemical Problems of Mineral Processing, 49, 2, 2013, 689-700. https://doi.org/10.5277/ppmp130227

12. A.M. Rashad, A synopsis about perlite as building material - A best practice guide for Civil Engineer, Construction and Building Materials, 121, 2016, 338-353. https://doi.org/10.1016/j.conbuildmat.2016.06.001

13. L. Lakov, B. Jivov, Y. Ivanova, K. Toncheva, Performance Characteristics of a Modified Composite Material Containing Inorganic Lightweight Aggregates, J. Chem. Technol. Metall., 59, 6, 2024, 1407-1414. https://doi.org/10.59957/jctm.v59.i6.2024.16

14. D.V. Makarov, N.K. Manakova, O.V. Suvorova, Production of Rock-Based Foam-Glass Materials (Review), Glass and Ceramics (English translation of Steklo i Keramika), 79, 9 - 10, 2023, 411-417. https://doi.org/10.1007/s10717-023-00522-8

15. P.I. Urkimbayeva, B. Bakytzhanuly, L.M. Tugelbayeva, K.M. Al Azzam, Sh.O. Yespenbetova, G.A. Mun, Z.A. Kenessova, E.E. Dilmukhambetov, E.-S. Negim Influence of Polyvinyl Alcohol-Based Copolymers on the Physico-Mechanical Properties of the Thermal Insulation Materials, J. Chem. Technol. Metall., 57, 6, 2022, 1122-1128.

16. S. Shenoy, A. Mahshook, A. Kumar Bhat, S. Kabeer Ahmed, Performance Study on Laterite Block with Perlite IOP Conference Series: Earth and Environmental Science, 1387, 1, 2024, 012009. https://doi.org/10.1088/1755-1315/1387/1/012009

17. S. Abdelaal, A.M. Elkatatny, Abdel Fattah, Perlite incorporation for sedimentation reduction and improved properties of high-density geopolymer cement for oil well cementing, Scientific Reports, 14, 1, 2024, art. no. 9707. https://doi.org/10.1038/s41598-024-60587-5

18. A. Wolfthaler, P. Harsányi, M. Schneider, Development and Performance of High Strength Lightweight Concrete with Perlites, Lecture Notes in Civil Engineering, 392 LNCE, 2024, 126-133. https://doi.org/10.1007/978-3-031-44603-0_12

19. D. Diekman, Overview and end uses of perlite. Society of Mining Engineers of AIME, 85-350, 1986, 1-2.

20. F.L. Jackson, Processing Perlite for Use in Insulation Applications, Transactions of the American Institute of Mining, Metallurgical and Petroleum Engineers, Society, 280, pt A, 1986, 40-45.

21. Y. Şahin, Y. Gündüz, PCMs with perlite aggregate for snow melting applications, Sustainable Energy Technologies and Assessments, 62, 2024, 103617. https://doi.org/10.1016/j.seta.2024.103617.

22. I.E. Kalafatoğlu, T. Ayok, N. Örs, Filtration of borax solutions through perlite, Chemical Engineering and Processing: Process Intensification, 33, 3, 1994, 151-159, https://doi.org/10.1016/0255-2701(94)90005-1.

23. F.I. Majorov, A.V. Grishchenko, S.V. Kostrykin, Reducing slag inclusion related rejects and enhancing lining durability when using perlite rock, Litejnoe Proizvodstvo, 5, 2005, 6.

24. Z. Zawieja, J. Sawicki, Thermogravimetric analysis of modified cellulose mixtures in air, Archives of Metallurgy and Materials, 64, 1, 2019, 153-157. https://doi.org/10.24425/amm.2019.126231

25. B. Silber, I. Bar-Yosef, Levkovitch, S. Soryano, pH-Dependent surface properties of perlite: Effects of plant growth, Geoderma, 158, 3-4, 2010, 275-281. https://doi.org/10.1016/j.geoderma.2010.05.006.

26. Yu.I. Tarasevich, S.V. Bondarenko, K.A. Zabela, A.V. Nazarenko, L.K. Patyuk, Patent RU2055637C1 (10.03.1996), Russia, A method for obtaining a hydrophobic adsorbent for the extraction of petroleum products from aqueous media, (in Russian).

27. Z. Khoshraftar, H. Masoumi, A. Ghaemi, On the performance of perlite as a mineral adsorbent for heavy metals ions and dye removal from industrial wastewater: A review of the state of the art, Case Studies in Chemical and Environmental Engineering, 8, 2023, 100385. https://doi.org/10.1016/j.cscee.2023.100385.

28. M. Malakootian, N.-A. Jaafarzadeh, H. Hossaini, Efficiency of perlite as a low-cost adsorbent applied to removal of Pb and Cd from paint industry effluent, Desalination and Water Treatment, 26, 1-3, 2011, 243-249. https://doi.org/10.5004/dwt.2011.1748.

29. G.V. Shvedchikov, Patent RU2255804C1 (10.07.2005), Russia, A method for producing a sorbent for petroleum, petroleum products and liquid hydrocarbons, (in Russian).

30. V.G. Pajchev, M.S. Poluhin, S.F. Shmot'ev, S.Yu. Pliner, E.V. Rozhkov, V.M. Sychev, Patent RU2531966C1 (27.10.2014), Russia, The method of complex processing of perlite, (in Russian).

31. V.G. Pajchev, M.S. Poluhin, Patent RU2531970C1 (27.10.2014), Russia, A method for manufacturing

a hydrophobic lightweight microsphere based on perlite, (in Russian).

32. R.G. Melkonyan, Theoretical foundations of the hydrothermal-alkaline method of processing perlite rocks, Mining information and analytical bulletin, 12, 2001, (in Russian).

33. S.A. Sagarunyan, M.M. Makaryan, A.G. Arustamyan, E.M. Nazaryan, A.S. Sagarunyan, Research of processes and development of technology for complex processing of perlite, Proceedings of the Kola Scientific Center of the RAS, 5, 31, 2015, (in Russian).

34. V. Shevko, N. Mirkayev, B. Lavrov, A. Badikova, Obtaining A Silicon Alloy from A Sedimentary Rock - Tripoli, J. Chem. Technol. Metall., 58, 2, 2023, 367-375.

35. V.M. Shevko, N.M. Mirkayev, A.D. Badikova, Kinetics of silicon extraction into alloy from a mixture of amorphous rocks, Journal of Alloys and Metallurgical Systems, 10, 2025, 100184. https://doi.org/10.1016/j.jalmes.2025.100184

36. V.M. Shevko, N.M. Mirkayev, D.K. Aitkulov, A.D. Badikova, Producing a siliceous ferroalloy from a mixture of amorphous rocks, Results in Engineering, 23, 2024, 102754. https://doi.org/10.1016/j.rineng.2024.102754

37. HSC Chemistry Software, Metso Outotec, Pori 2021. https://www.metso.com/portfolio/hsc-chemistry/?r=3, accessed on 2nd May 2025.

38. V.N. Shklyar, Experimental planning and results processing, National Research Tomsk Polytechnic University, Tomsk, 2010, (in Russian).

39. A.I. Stroganov, M.A. Ryss, Production of steel and ferroalloys, Moscow, The Alliance, 2017, (in Russian).

40. V.G. Voskobojnikov, V.A. Kudrin, A.M. Yakushev, General metallurgy, Textbook for universities, Metallurgy, Moscow, 1979, (in Russian).

41. A.M. Inkov, T. Tapalov, U.U. Umbetov, H.W. Tsen., K.T. Akhmetova, E.T. Dyakova Optimization methods: e-book, Shymkent, SKGU, 2003, (in Russian).

42. V.V. Glukhikh, A.Ye. Shkuro, A.V. Artemov, Mathematical planning of experiments and analysis of their results using computer programs, Ural State Forest Engineering University, Yekaterinburg, 2023, (in Russian).

43. State standard 1415-93 Ferrosilicon. Technical requirements and terms of delivery, Moscow, Standartinform, 2011, (in Russian).

44. Technical Specifications 0820-011-14513884-2013, Ferrosilicon aluminum, UIS LLC, Ekaterinburg, 2013, (in Russian).

45. W. Pichór, A. Janiec, Thermal stability of expanded perlite modified by mullite, Ceramics International, 35, 1, 2009, 527-530. https://doi.org/10.1016/j.ceramint.2007.10.008.

46. J. Dzięcioł, O. Szlachetka, J.M. Rodrigues Tavares, From volcanic popcorn to the material of the future: A critical review of expanded perlite applications and environmental impacts, Sustainability, 17, 4, 2025, 1454. https://doi.org/10.3390/su17041454