Study of silicon production process in ore-smelting furnace and optimization of technological process

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ABSTRACT

This article presents the results of production experiments to optimize the modes of silicon smelting in an industrial arc furnace. The main factors of the melting process are the size of the fractions of the charge components and the temperature regime of heating. The rate of charge heating in the reaction zone in the temperature range from 950 to 14100C has a special effect on productivity. In this temperature range, the formation of refractory silicon carbide on pieces of quartzite was established, which causes a drop in the magnitude of the electric current in the reaction zone and its freezing. The gornisage, which is formed, displaces the electrodes into the zone of greater charge electrical conductivity - up, which leads to an increase in silicon monoxide emissions through the reduced charge layer. Correction of such a process requires an increase in the temperatures in the reaction zone and the duration of the melt. A method has been developed for calculating the size of quartzite fractions, depending on the power of the furnace and the size of the reaction zone. An example of a simplified calculation is proposed.

Keywords: Silicon, quartzite, coke, carbide, monoxide, arc furnace

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Introduction

The practical value of such optimization is lost due to the inadequacy of the recommended modes to practical results [1]. This publication analyzes this conclusion, undeserved by thermodynamics, and provides an example of industrial studies explaining such a delusion. Industrial experimental studies were carried out on an electric arc silicon furnace with a power of 1.8 kVA (2 kW). The reasons for the furnace freezing were determined and a solution to the problem is proposed by optimizing the fractional composition of the charge components and adjusting the modes of conducting the melting process.

Experimental part

The study of high-temperature reduction processes is a technically and economically difficult task. For this reason, researchers in the field of

carbothermal reduction of silicon from quartzites take the results of thermodynamic modeling as a basis. Existing computer programs for thermodynamic analysis do not allow taking into account the reality of changing conditions in the system. And, experiments, apparently, are also carried out "virtually". This opinion was formed since in practice, especially when starting new silicon productions and when changing raw materials, such recommendations turn out to be useless for production technologists. The authors were convinced of this when launched the production of silicon from quartzites of South Kazakhstan in the metallurgical shop of StekloK LLP.

In the production of metallurgical silicon, problems arose, leading to the "freezing" of the reaction zone in the furnace hearth, the displacement of electrodes by the furnace encrustation consisting of a mixture of silicon carbides, inclusions of polycrystalline silicon, oxides, and inclusions of coke (Figure 1). Such an accident in production leads to an increase in energy costs for process corrections and, in the worst case, to a forced shutdown of the melting process. According to the terminology of metallurgists, this is the formation of a "bear" in the furnace [bear – metal frozen in the volume of the furnace or ladle as a result of a violation of the normal technological process course or an emergency release of metal from the furnace or pouring ladle. [http://metaltrade.ru/ abc/a.htm].

The photo in Figure 1 shows a piece taken from a "frozen" silicon furnace – the lower part of the piece, lighter, is a solidified mixture of silicon crystallites, silicon carbides and oxides. And the upper part is a partially melted charge – a mixture of coke, quartzite and reduction products: carbides, silicon monoxide and silicon crystallites.

Specialists when developing technological modes of the carbothermal process of silicon reduction from quartzites use the results of thermodynamic analysis, including thermodynamic modeling [[1], [2], [3], [4], [13], [19]]. It should be understood that thermodynamic studies allow to assess the possibility of implementation, however in practice it is very problematic to obtain the expected result according to the thermodynamic analysis without adjustment, taking into account specific processes in the furnace.

The reasons for this problem lie in the fact that in a real process there are changes in the component composition in the system, temperature changes in the contact zones of the

system components, which create kinetic obstacles to mass transfer processes in the reaction zone of the furnace. For example, in a system of charge consisting of pieces of quartzite, coke, coal, wood chips [5], intermediate chemical compounds are formed at the boundary between the reagents in the reaction zone of the furnace, changing the component composition of the system, therefore, the thermodynamic conditions for chemical reactions change. Taking into account the changing conditions of the system's thermodynamic state is a very difficult and not yet solved problem in modeling heterophase multicomponent systems.

Figure 1 - Photo of the frozen part of the charge and the furnace encrustation in an industrial arc furnace: crystallized mixture of silicon carbide with inclusions of silicon and quartzite (silicon oxides) reduced by 20 times M1:20

In this article, the authors consider the process that occurs in an industrial silicon arc furnace, studied by industrial experiments.

The efficiency of silicon reduction melting in an electric arc ore-smelting furnacedepends on many interdependent factors: the fractional size of the charge components, the homogeneity of the charge components' distribution, the temperature in the reaction zone, the duration of reaching the temperature condition for the main process – theprocess of silicon formation. Let us omit the elemental and phase composition of the charge components from discussions, since many scientific works are devoted to this [[6], [7], [8], [12], [13], [14], [17]]. This publication discusses the results of studying technological factors that affect the

effectiveness of the metallurgical process for obtaining metallurgical silicon from quartzites. It is known [[9], [10], [13], [18], [19], [20]] that the production of silicon by the carbothermal method is carried out according to the main four reduction process stages. In the process of moving the charge from the top zone to the electric arc furnace hearth, the charge components are heated by gases sublimated from the reaction zone, in which the temperature reaches 2000-3000°C. The industrial experiments were carried out on an industrial three-electrode furnace with electrodes buried in the charge by 1.2-1.5 m:

Stage 1. Heating the mixture with hot gas – sublimates from the furnace reaction zone, consisting of carbon monoxide (CO), carbon dioxide (CO_2) and silicon monoxide (SiO).

It is known [11] that a chemical reaction occurs at the boundary of the solid phase with the gaseous phase:

$$CO + CO = CO_2 + C \qquad (1)$$

The resulting atomic carbon has an increased activity, which was confirmed in practice and used for a long time in the technology of carburizing parts from structural steels in mechanical engineering. This happens at a temperature of 940°C [9].

The formation of an active reducing agent, atomic carbon, provides the conditions for the reactions:

$$SiO_2 + C = SiO + CO \qquad (2)$$

$$SiO + C = Si + CO \qquad (3)$$

The products of reactions (2) and (3): SiO and CO are gaseous, and Si is condensed under these temperature conditions, SiO and Si are adsorbed on the charge components' solid phasesurface: quartzite, coal and coke pieces (Figure 2) and the gaseous product, carbon monoxide gas (CO), reacts (1), and unreacted carbon monoxide and silicon monoxide (SiO) above the top surface interact with atmospheric oxygen to form carbon dioxide CO_2 and SiO_2 – carbonwhite.

Stage 2. Silicon formed as a result of reaction (3) is adsorbed by the charge components' surface and forms a film in the temperature range 950°C – 1410°C (up to the melting temperature of silicon – 1410°C).

In this temperature range, atomic carbon and a silicon film are converted into a silicon carbide shell according to reaction (4) Figure2:

$$Si + C = SiC \qquad (4)$$

The process of silicon reductionfrom quartzite at this stage is determined by the carbon atoms' diffusion rate through the shell of silicon and silicon carbide, let's call it "shell". The shell is a sufficiently strong and refractory screen between the reagents (the melting point of silicon carbide is above 2730°C [10]). With the melting of the quartzite pieces inside the shell (the melting temperature of which is above 1750°C), a change in the density of quartzite occurs, as a result of which the shell is destroyed – itcracks if it is not strong enough, which depends mainly on the shell thickness.
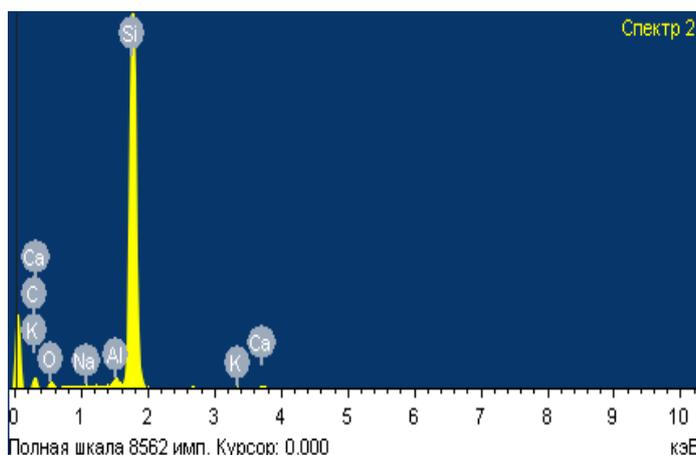

a)   b)

Figure 2 - Photo of the quartzite piece extracted from the upper zone of the furnace shaft at a depth of 0.5-0.6 m from the top:
a) a sample of quartzite coated with a thin layer of silicon and soot (carbon),
b) spectrum from light areas with a blue tint (the most intense peak of the silicon spectrum)

With the melting of quartzite, the aggregate composition of the components in the system changes. The system, which consisted of solid and gaseous reagents, is transformed into a system: liquid – gas. Such changes in the system conditions provide an increase in the rate of chemical processes and implementation of chemical reactions (2), (3) and reaction (5):

$$2SiC + SiO_2 = 3Si + 2CO \qquad (5)$$
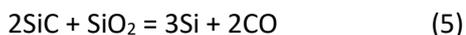
The resulting liquid silicon flows down to the furnace bottom, where it accumulates and after a certain time the silicon melt is poured from the furnace into the ladle.

In addition to the shell formation on the quartzite pieces, reactions (3) and (4) also occur on the reducing agent surface: pieces of coke and coal, since SiO at temperatures exceeding the condensation temperature of gaseous silicon monoxide is adsorbed by coke and coal.

The result of these processes is the formation on the charge pieces' surface of a film of silicon and then silicon carbide, which have a lower electrical conductivity, this is accompanied by a decrease in the electrical conductivity of the charge. The consequence of such a change in the charge composition and the intermediate products' properties is a decrease in the electric current value in the reaction zone of the main heat source, the result of this is a decrease in temperature in the reaction zone. In support of what – Figure (a)with the quartzite piece coated with silicon carbide. A very interesting fact was the discovery of the formation of carborundum in the form of needle-shaped crystals similar to twigs – dendritesin the frozen reaction zone of the furnace (Figure 2b). This fact indicates the crystallization of silicon carbides from the gas phase – crystallizationof carborundum dendrites occurs on the surface of the formed SiC layer as a result of reactions (1), (2), (3) and (4).

Under these temperature conditions, CO, SiO are gas phases, and C, Si, SiC are condensed phases.

The silicon reduction process abnormalityin the furnace can be excluded if the technological parameters are strictly observed: the charge fractions' size, the current density in the reaction zone and the temperature, which should be higher than the melting point of quartzite – above1750°C (Since meltedquartzite has a high dynamic viscosity, the heating temperature should be significantly higher than the melting point of quartzite). Therefore, the electric power in the furnace hearth

should provide the possibility of increasing the electric voltage to maintain the current density in the reaction zone at the required level, which is determined by the quartzite fractions' sizein the charge.

Figure 3 - Quartzite coated with silicon carbide during silicon carbothermy in an electric arc furnace

As a result of these chemical processes in the reaction zone of the furnace, the "shell" becomes sufficiently strong, the active electrical resistance of the charge increases, the electric current between the electrodes decreases, the furnace encrustation is formed on the furnace hearth, the furnace electrodes are forced upwards into the more electrically conductive part of the charge, and on the hearth there is a freezing of "slag-carborundum" – amixture of quartzite, silicon and carborundum (Figure 4).

Figure 4 - Photo of the furnace encrustation pieces – Slagcarborundum from the "frozen" furnace

The algorithm for solving this complex multi-factorial problem is as follows:

1. Taking into account the peculiarity of the carbothermal process in a silicon ore-smelting furnace, where the reaction zone is under a layer of charge with electrodes buried in the charge, its sizes and shape are determined by the interelectrode space with the temperature range of more than 1750° C – thescheme is shown in Figure 5.

The production process can be with a continuous discharge of the silicon melt, however in practice it took root periodically, that is, at the beginning, the silicon melt is accumulated in the furnace, then the melt is released (discharged) into a ladle for refining by blowing with oxygen and pouring into molds. Therefore, the process is carried out in cycles. The temperature mode in the furnace hearth is shown in Figure 6.

After discharging the silicon melt from the furnace, the charge is deposited in the hearth. The temperature of the charge entering the reaction zone of the furnace should be 950...1000°C. The authors recommend pushing the charge prepared for loading into the furnace for the next cycle from the top zone sides to the top center, while maintaining the components' distribution homogeneity in the charge. The charge enters the hearth in each subsequent cycle with a temperature not lower than 950...1000°C.
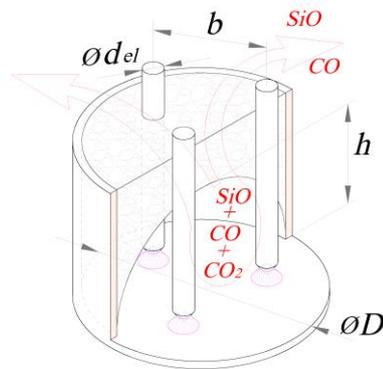

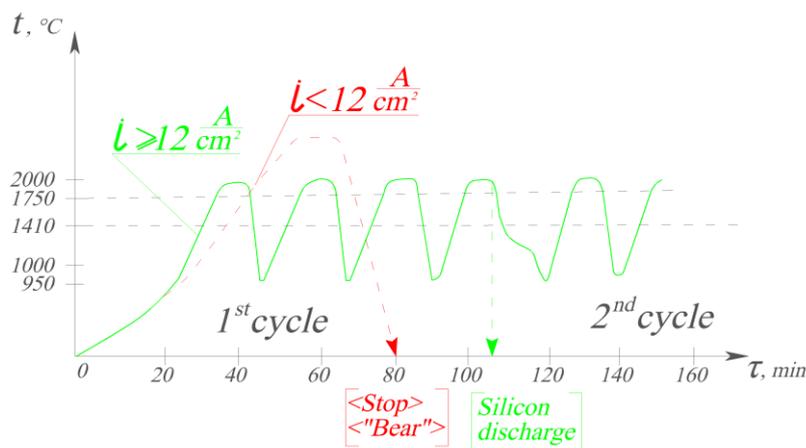**Figure 5** - Scheme of the reaction zone in the carbothermal furnace

Figure 6 - Temperature mode in the reaction zone of the silicon carbothermal furnace:
Red line – the heatingmode at the current density
less than 12A/cm^2,
leading to the furnace freezing;
Blue line – the heating mode at the current density greater than 12A/cm^2
(for experiments in the studied production conditions –
the furnace with the power of 2 kW or 1.8 kVA)

In the furnace hearth, the most important and responsible process for melters begins: chemical reactions (2, 3 and 4), it is necessary to prevent the formation of a critical layer on the quartzite pieces – "shells" of silicon carbide.

Important technological parameters in this process are the quartzite pieces' sizesin the charge and the duration of their melting in the reaction zone. The duration of heating until the melting of the quartzite pieces provides the conditions for the formation of the "shell"from SiC. The intensity of heating the quartzite pieces in the reaction zone depends on the current density in the reaction zone.Coarse fractions take longer to heat up, therefore, the duration of heating to the melting temperature of quartzite increases, creating conditions for the "shell" formation.

The charge's fine fraction has a low gas permeability, which contributes to the formation of wormholes (a powerful torch from the reaction zone, as a rule, along the electrodesurfaces). This leads to thermal energy losses in the reaction zone and the release of CO and SiO. Therefore, from this point of view, the determining indicator of the charge fractions' sizes is the provision of gas permeability. The larger the quartzite fraction, the higher the charge's gas permeability, and on the other hand, with large quartzite fractions, it is more likely to get "shells" from silicon carbides on the quartzite pieces,which increases the charge's electrical resistance, and reduces the electric current value in the hearth, therefore, reduces the temperature in the reaction zone – fromwhich the furnace "freezing" begins, that is, the "bear" formation.

Figure 7 - Photoof the carbothermal furnace, used in the experiments

In the industrial experiments in the furnace with the power of 2 MW (Fig. 7), the authors experimentally established: for quartzite – piecesin cross section should be from 50 mm to 110 mm, for coke – from20 to 50 mm. The task is to calculate the heating time of the quartzite pieces in the reaction zone – abovethe melting temperature, taking into account the quartzite melt viscosity, the temperature should be above 1750°C.

Results and Discussion

Simplified calculation of the heating time of the quartzite pieces in the reaction zone before the melting:

Step 1. Determining the reaction zone size (see Figure 3). The volume under the dome is calculated using formula 1.1 [6]:

$$V_{rz}= \pi h^2(D/2 – h/3) \qquad (1.1)$$

where: V_{rz} – the volume under the reaction zone dome; π – geometric constant ~ 3.14 – the ratio of the circumference to the diameter; D – the diameter of the working furnace hearth space, m; h – the reaction zone dome height, m.

For approximate calculations, it is possible to take the reaction zone dome height equal to $D/2$. In the experiments, according to the results of measurements of "frozen" working areas, $h = 0.5$-$0.7D$. For approximate calculations of the charge mass in the reaction zone, it is necessary to take into account that part of this volume is occupied by the graphite electrodes of the furnace.

Example: In the ore-smelting furnace with the power of 2 MW, $D = 1.75$ m, $h = 1.05$ m, according to the results of measurements of the melted and "frozen" zones in the furnace, the reaction zone volume was determined to be $1.8 – 2.02$ m^3.

Step 2. Based on the bulk density of the charge and its composition, the authors determine the charge mass in the reaction zone – $G_{charge\ rz}$, which occupies the reaction zone volume in the furnace hearth. With an average bulk density g_{bulk} of the charge in the industrial experiments equal to 0.85–0.90 t/m^3:

$$G_{charge\ rz}= g_{bulk}V_{rz}$$

The reaction zone volume occupied by the electrodes is approximately 30%. Therefore, the charge volume in the reaction zone will be $0.7V_{rz}$.

In the example under consideration: $G_{charge\ rz}= g_{bulk}0.7V_{rz} = 2.02·0.7·0.85 = 1.19$ t.

Step 3. Knowing the charge mass and composition in the reaction zone, the authors perform an approximate calculation of the energy costs for heating quartzite in the charge and the entire charge from 950°C to 1750°C.

The energy required to heat the charge is very difficult to determine according to the laws of heat transfer [[7], [8], [9]], in this case, there is no need for an accurate calculation, therefore, the calculation is limited to determining the difference between the heat content of the charge components at 1750°C and 950°C, taking into account the furnace efficiency.

Taking into account the fact that intensive mass transfer of the process of silicon reduction from quartzite occurs after the melting of quartzite, the authors assume that the quartzite mass changes insignificantly. Then the amount of thermal energy required to achieve the melting temperature of quartzite in the charge:

$$\Delta Q_{charge\ rz} = G_{quartzite\ rz} \cdot (C_{quartzite\ 1750} - C_{quartzite\ 950}) + G_{coke\ rz} \cdot (C_{coke\ 1750} - C_{coke\ 950}) + G_{coal\ rz} \cdot (C_{coal\ 1750} - C_{coal\ 950})$$

Where: $\Delta Q_{charge\ rz}$ – change in the heat content of the charge in the reaction zone during heating from 950 to 1750°C; $Q_{charge\ rz\ 1750}$, $Q_{coke\ 1750}$, $Q_{coal\ 1750}$ – the heat content of quartzite, coke and coal in the reaction zone at 1750°C; $Q_{charge\ rz\ 950}$, $Q_{quartzite\ 950}$, $Q_{coke\ 950}$, $Q_{coal\ 950}$ – the heat content of quartzite, coke and coal in the reaction zone at 950°C; $C_{quartzite\ 1750}$, $C_{quartzite 950}$, $C_{coke\ 1750}$, $C_{coke\ 950}$, $C_{coal\ 1750}$, $C_{coal\ 950}$ – the heat capacity coefficients of quartzite, coke, coal, respectively, at 1750 and 950°C.

Step 4. The authors determine the time required to heat the charge in the reaction zone to 1750°C. Knowing the nominal power of the furnace and the efficiency, it is possible to determine the useful power of the furnace, that is, the power that is spent on heating the charge in the reaction zone. The efficiency according to the furnace passport is η=0.60, therefore

$$P_{useful} = P_{nominal} \cdot \eta = P_{nominal}0.60$$

The heating time (approximate) of the charge in the reaction zone (τ) is calculated as follows:

$$\tau = \Delta Q_{charge\ rz} / P_{useful}, c$$

Step 5. The authors determine the duration by the time required for the formation of the "shell", which reduces the electrical conductivity of the charge, which is easy to control by the readings of the ammeters on the control panel. An increase in the active electrical resistance of the charge reduces the current density in the reaction zone, and the result of such a change in the process is "freezing" in the reaction zone.

Figure 6 shows the scheme of the temperature mode in the reaction zone of the carbothermal furnace. The mode was selected experimentally.

For the practical use of the industrial experiment results, the authors present a simplified calculation of the optimal size of the quartzite pieces in the charge according to the maximum allowable duration of their heating until the melting in the furnace hearth zone from 950°C. During this duration – the time of heating the quartzite piece, its heat content should increase from $Q_{950°C}$ to $Q_{1750°C}$:

$$Q_{950°C} = C_{1123K} \times M_{quartzite\ piece} \times T_{start}$$
$$Q_{1750°C} = C_{2023K} \times M_{quartzite\ piece} \times T_{end}$$

Where: C_{1123K}, C_{2023K} – the heat capacity of quartzite at 950°C and 1750°C; $M_{quartzite\ piece}$ – the mass of the quartzite piece in the charge, to simplify calculations, let's take the form of the quartzite pieces as spherical, $M_{quartzite\ piece} = V_{quartzite} \times \rho_{SiO2}$, where: $V_{quartzite}$ – the volume of the quartzite piece in the charge, for a sphere – $2\pi R^3/3$, ρ_{SiO2} – the specific gravity of quartzite.

The difference between the heat content of the quartzite piece from $Q_{1750°C}$ to $Q_{950°C}$ is the amount of energy $\triangle Q$ that must be transferred to the quartzite piece in the furnace hearth for a limited time – this is the time during which the "shell" of critical thickness does not have time to form.

Observations of the melting process in the ore-smelting furnace allow to establish the duration of the charge melting from the start of filling the reaction zone with the charge to its melting with different current densities at the furnace electrodes. The current density (i) in the reaction zone of the furnace is controlled by the operator, by changing the voltage on the furnace electrodes and by changing the electric current value between the electrodes by their immersing into the reaction zone. Taking into account that the nominal power of the furnace is as follows:

$$P_{nominal} = I \cdot U, W$$

The electrical conductivity in the reaction zone also depends on the component composition of the charge, that is, the proportion of electrically conductive components: coke, coal, and the degree of gas ionization ($SiO + CO + CO_2$) in the reaction zone. The current density on the electrodes has a limiting value and depends on the electrode material. It is known that graphite electrodes provide the highest current density, for example, for electrodes with a diameter of 250 mm, the maximum allowable current density is 21 A/cm^2.

$$I_{nominal} = P_{nominal} / U \cdot S_{el} = I \cdot U / U \cdot S_{el} = I / S_{el}$$

Where: i – the electric current density in the reaction zone, A/cm^2; U – the electrical voltage on the electrodes, V; S_{el} – the electrode surface area located in the reaction zone of the furnace, cm^2, I – the electric current value in the reaction zone, A.

The heating time of the quartzite piece in the reaction zone before the melting, that is, up to 1750°C, can be approximately calculated by dividing the amount of energy spent on heating the quartzite piece to 1750°C by the thermal energy perceived by the quartzite piece surface:

$$T_{heating\ the\ quartzite\ piece} = \triangle Q_{quartzite\ piece} / i \cdot U \cdot S_{quartzite\ piece}$$

Where: $\triangle Q_{quartzite\ piece}$ - the amount of energy that must be transferred to the quartzite piece for its melting in the reaction zone – spent on heating the quartzite piece in the reaction zone from 950°C to 1750°C; $S_{quartzite\ piece}$ – the quartzite piecesurface area. Let's take a sphere for the shape of the quartzite pieces, then $S_{quartzite\ piece} = \pi d^2$, cm^2.

The quartzite piece heating rate in the furnace hearth is carried out by radiant energy and thermal energy transfer by thermal conductivity from the quartzite piece surface to its center. Therefore, to ensure heating of the quartzite piece in the reaction zone of the furnace, the quartzite's thermal conductivity plays a decisive role in the heating rate. This is clearly seen from the calculation results (Table 1)

$$\tau_{heating\ the\ quartzite\ piece} = \triangle Q_{quartzite\ piece} / i \cdot U \cdot \pi d^2_{quartzite\ piece}$$

Let's transform this formula to calculate the cross-section size of the quartzite pieces in the charge:

$$d_{quartzite\ piece} = (\triangle Q_{quartzite\ piece} / i \cdot U \pi \tau_{heating\ the\ quartzite\ piece})^{-2};$$
$$i_{quartzite\ piece} = \triangle Q_{quartzite\ piece} / \tau_{heating\ the\ quartzite\ piece} \cdot U \cdot \pi d^2_{quartzite\ piece},$$
$$i_{nominal} = P_{nominal} / U \cdot S_{el}$$

Let's set the cross-section sizes of the quartzite pieces in the charge and calculate the corresponding values of the electric current density in the reaction zone of the carbothermal furnace.

Analysis of the results of these calculations shows that it is energetically more profitable to process a fine fraction than a coarse fraction of quartzite, this is without taking into account heat losses to the environment and losses on the duration of the process due to the low thermal conductivity of quartzite, due to which the duration of melting of large quartzite fractions increases to 1750°C – temperature of liquid-phase reduction of silicon.

Table 1- Calculation results of energy costs for melting the quartzite piece in the charge of the arc ore-smelting furnace

$d_{quartzite piece}$, cm	5	10	20	30	40
$R_{quartzite piece}$, cm	2.5	5	10	15	20
$\tau_{heating the quartzite piece}$, C	0.36	72	1.433	433204.9/3.5 min	274.3/4.6 min
$i_{quartzite piece}$, A/cm^2	1.22	2.44	4.88	7.32	9.76
$V_{quartzite piece}$	32.656	261.7	2093	7053.75	16746
$M_{quartzite\ piece} = V_{quartzite} \times \rho_{SiO2} 10^{-3}$, kg	84.9	680.42	5441.8	18339.75	43539.6
$\triangle Q_{quartzite piece}$, J	59.43	476300	3780926	12833.8	30539.6

Example of approximate calculation of the technological parameters of a carbothermal process in a 2 MW furnace

Calculation of sizes of the reaction zone

Knowing the geometrical parameters of the furnace: the electrodes' diameters d_{el}, the electrodes' decay diameter D_{decay}, the furnace bottom diameter (the furnace top diameter) $D_{furnace}$, it is possible to calculate the volume of the reaction zone. But for this it is necessary to determine the area above the top (above the furnace hearth) with a temperature – abovethe quartzite's melting temperature, we chose a zone with frozen pieces of charge with melted traces. As a result, a dome with a height of 650-700 mm was determined (see Figure 4).

Approximately the volume of such a dome can be calculated by the formula:

$$V_{rz} = \pi h^2 (D_{furnace\ hearth}/2 - h/3) \qquad [6]$$

Where: V_{rz} – the dome volume – the reaction zone of the carbothermal furnace;

π- $\approx 3.1415926535 \approx 3.14$; h – the dome height, m; $D_{furnace\ hearth}$ – the furnace hearth diameter, m.

For the furnace in our experiments:

$$V_{rz} = 3.14 \cdot 0.7^2 \cdot (1.0/2 - 0.7/3) = 0.41 m^3$$

The charge volume in the reaction zone is less by the volume occupied by the furnace electrodes. Therefore, the volume occupied by the charge in the reaction zone will be: $V_{chrz} = V_{rz} - V_{erz}$; $V_{erz} = 3\pi d_{el}^2 \cdot h_{erz}/4$

Multiplying the value of the charge bulk density g_{bd} ($g_{bd} = 0.9$ t/m^3) by the reaction zone volume, we determine the charge mass in the reaction zone M_{chrz}.

$$M_{chrz} = V_{rz} \cdot g_{bd}$$

Knowing the charge composition in the reaction zone, taking into account the fact that wood chips in the charge completely burn out inthe reaction zone, the charge consists of quartzite, coke, coal and charcoal (in our experiments, coal from Shubarkul deposit was used instead of charcoal – itsproperties are close to charcoal).

$$M_{chrz} = V_{rz} \cdot g_{bd} = 0.41 \cdot 0.9 = 0.369 t = 369 kg$$

Next, we calculate the percentage composition of the charge in the reaction zone, the zone where the temperature reaches the melting temperature of quartzite. Then we determine the mass content of the charge components in the reaction zone. In our experiments, the calculated composition was verified by chemical analysis of samples from the frozen reaction zone. The content, mass %, were determined: quartzite 51-53, oil coke and coal 17-19, Shubarkul coal 30-32. The calculated mass of the charge ($M_{chrz} = 369$ kg) was distributed according to the percentage values of their content and obtained that in the reaction zone in our furnace, in kg: quartzite 191-192, coal and coke combined 66-69, Shubarkul coal 111-113. It was difficult to analytically separate coal and coke in the frozen part of the reaction zone. We combined all reducing agents into one numerical value $V_{reduction} = 177$ kg with the quartzite mass 192 kg.

We calculate the change in the heat content of the charge in the reaction zone by the average value of the specific heat of the charge components (for accurate calculation, it is necessary to calculate the change in the heat content in the reaction zone for each component of the charge and then sum it up). Taking into account that the coefficients of specific heat capacity of the components differ little and our calculation is approximate, we took $C_{thermal} = 1.3$ kJ / (kg $\cdot$ °C). [10].

To heat the charge in the reaction zone from 950°C to 1750°C, it is necessary:

In our experiments: $Q_{chrz} = M_{chrz} \cdot C_{thermal} \cdot (1750-950) = 369 \cdot 1.3 \cdot 800 = 383760$ kJ

The furnace power taking into account its efficiency, $\eta = 0.60$– usefulpower, $P_{useful} = 2 \cdot 10^6 \cdot 0.60 = 1.2 \cdot 10^6$ W $= 1.2 \cdot 10^3$ kW

The charge heating time in the reaction zone from 950°C to 1750°C is calculated by the formula:

$\tau = Q_{chrz} / P_{useful} = 383760 / 1.2 \cdot 10^3 = 319.8$ s $= 320$ s $= 5.3$ min

With such a power of electric current, the voltage between the electrodes was 90-100 V, the current density on the electrode was 12.2 A/cm^2.

Conclusion

A set of studies performed on the industrial ore-smelting furnace with the capacity of 2 MW for production of silicon allows us to conclude the following:

1. The most important factors determining the success of the efficient production of silicon by the carbothermal method in the electric arc furnace:

- the size and shape of the charge components, which depend on the furnace power and the maximum allowable electric current density on the electrodes;

- the temperature in the reaction zone of the furnace must be higher than the melting temperature of quartzite;

- the important technological parameter is the duration of heating the charge in the range: 950-1750°C – the temperature range of the shell formation containing silicon carbides.

2. In the reaction zone for the implementation of a chemical reaction: $SiC + SiO_2 = 2Si + CO_2$, temperature should exceed 2250°C [7], and this is an increase in the specific energy consumption for obtaining the product, therefore, to ensure this condition, it is necessary to carry out the silicon reduction process with a minimum amount of silicon carbide formed, which is formed in the temperature range of 950-1750°C. Therefore, the heating of the charge in this temperature range should be carried out in a minimum time, the possibility of this is ensured by the maximum allowable current density for the electrodes, in our experiments it is 12.5 A/cm^2, and by upsetting the charge into the reaction zone with the help of crush (a mechanism for upsetting and crushing sintered pieces from the charge) every 20-30 minutes of a "quiet" process with the obligatory "peaking" (piercing the charge layer with birch peaks) of the charge on the top for uniform gas permeation.

3. After the release of the silicon melt from the furnace and the collapse of the roof of the reaction zone to move the charge with the temperature of 950-1000°C into the reaction zone, it is necessary to switch the furnace to the maximum possible power for the period of time of melting the quartzite pieces in the reaction zone (in our experiments for 5.3 min – heating until melting the quartzite pieces and for the implementation of the main reactions of silicon reduction for another 10-20 minutes.

4. In the temperature range of 950-1000°C, the furnace should provide the maximum charge heating rate in the cyclic mode of unloading the product from the furnace (discharging the silicon melt). With the continuous release of the silicon melt from the furnace, it is necessary to maintain a mode with a current density on the electrodes above 12 A/cm^2. When the size of quartzite pieces in the charge is not more than 200 mm.

5. Do not allow the charge to enter the reaction zone with a temperature below 950°C.

Acknowledgments

Conflict of interest. Corresponding author declares that there is no conflict of interest.

Кен балқыту пешінде кремний өндіру процесін зерттеу және технологиялық процесті оңтайландыру

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ТҮЙІНДЕМЕ

Бұл мақалада өнеркәсіптік доғалы пеште кремнийді балқыту режимдерін оңтайландыру бойынша өндірістік тәжірибелердің нәтижелері берілген. Балқыту процесінің негізгі факторлары шихта компоненттерінің фракцияларының мөлшері және қыздырудың температуралық режимі болып табылады. 950-ден 1410^{0}С-қа дейінгі температура диапазонында реакция аймағында шихтаны қыздыру жылдамдығы өнімділікке ерекше әсер етеді. Бұл температура диапазонында кварцит бөліктерінде отқа төзімді кремний карбиді түзіледі, бұл реакция аймағындағы электр тогының шамасының төмендеуіне және оның қатуына әкеледі. Түзілген горнизаж электродтарды заряды жоғары электр өткізгіштік аймағына ығыстырады, бұл төмендетілген заряд қабаты арқылы кремний тотығы шығарындыларының ұлғаюына әкеледі. Мұндай процесті коррекциялау реакция аймағындағы температураларды және балқыма ұзақтығын арттыруды талап етеді. Пештің қуатына және реакция аймағының көлеміне байланысты кварцит фракцияларының мөлшерін есептеу әдісі әзірленді. Жеңілдетілген есептеудің мысалы ұсынылды.

Түйін сөздер: кремний, кварцит, кокс, карбид, оксид, доғалы пеш.

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Исследование процесса получения кремния в рудно-плавильной печи и оптимизация технологического процесса

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АННОТАЦИЯ

В данной статье представлены результаты производственных экспериментов по оптимизации режимов выплавки кремния в промышленной дуговой печи. Основными факторами процесса плавки являются размер фракций компонентов шихты и температурный режим нагрева. Особое влияние на производительность оказывает скорость нагрева шихты в зоне реакции в диапазоне температур от 950 до 14100°С. В этом интервале температур установлено образование тугоплавкого карбида кремния на кусках кварцита, что вызывает падение величины электрического тока в зоне реакции и ее замерзание. Образующийся горнисаж смещает электроды в зону большей электропроводности заряда – вверх, что приводит к увеличению выделения оксида кремния через слой пониженного заряда. Коррекция такого процесса требует повышения температур в зоне реакции и продолжительности плавки. Разработан метод расчета размеров фракций кварцита в зависимости от мощности печи и размера зоны реакции. Предлагается пример упрощенного расчета.

Ключевые слова: кремний, кварцит, кокс, карбид, монооксид, дуговая печь

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