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Controlled placement of electrodes in an ore-smelting furnace and its effect on the reaction zone

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Abstract
The paper discusses specifics of the process of carbothermic reduction of metallurgical silicon in ore-smelting furnaces. The reaction zone represents a heating area for the charge materials, formed around the electrodes in all electric furnaces, and facilitates the release of thermal energy by passing electric current through a resistance and/or by creating an electric arc, change in the aggregate state of the loaded materials (e.g., quartzite, bituminous coal, needle coke), and a complex of chemical reactions that occur within such materials. When properly controlled, the operating conditions of the ore-smelting furnace provide optimal specific performance relative to specific power consumption. However, in case of deviations, such as high or low placement of the electrodes, excess or lack of reducing agent in the charge material, furnace throat level being too high or too low relative to technical guidelines, electrode voltage imbalance, etc., the furnace performance can be significantly reduced due to a non-conformant granulometric composition. If the furnace is operated with such deviations for extended periods of time, an emergency shutdown may occur. If the power generated at the electrode is insufficient, the reaction zone becomes significantly narrower, this leads to a change in the rate of chemical reactions. The excessive power levels, on the other hand, may cause intensive entrainment of microsilica along with the formation of blowholes capable of disabling water-cooled panels or shutting down the furnace transformer due to an overload. The location of the reaction zone in the furnace space plays a key role in ensuring effective operation of the ore-smelting furnace. Shifting of the reaction zone upward or downward may result in the grade drop of metallurgical silicon and reduced performance of the furnace, which will subsequently increase the product cost.

Keywords Metallurgical silicon · Microsilica · Ore-smelting furnace · Control system · Electrode position · Reaction zone · Graphite electrode

Significance of the problem

In the production of metallurgical silicon in ore-smelting furnaces (OSF), baked graphite (carbon) electrodes (diameter—710 mm) are used. To provide a stable technological process, it is necessary to ensure optimal immersion of the electrode tips inside the furnace with a subsequent adjustment of the electrode embedment. The length of the electrode tips should be between 2700 and 2850 mm (from the lower edge of the contact plates to the lower end of the electrode). In order to maintain a constant distance between the furnace hearth

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and the electrode tip as it burns, an offset (slip) is performed by shifting the electrodes downward relative to the contact plates. The slip value (position control) depends on the quality of the charge materials and electrical parameters, and should be between 2 and 2.5 mm per 1 MW · h of consumed power. To prevent thermal stresses, the one-time slip value should be between 200 and 400 mm.

The electrode tip position is measured during a temporary shutdown or a scheduled preventive maintenance, especially if there has been an extended technological disruption of the furnace. The length is calculated based on the previous measurement, while taking into account the shifting distance of the electrode tip and power consumption. If necessary, the electrode length is increased and instructions are given to perform a forced slipping. Since the position of the electrode tip is only controlled periodically, and there is no system that would provide real-time data about this parameter, while the calculation of consumed electricity provides approximate data about the electrode burnout, there is a high probability of error. The *objective of this study* is to examine the main deviations from the OSF standard operating conditions, which can lead to disruption of the technological process, and to identify those deviations that are related to the position of the electrode tips in the OSF space and, hence, to the reaction zone, which determines the performance efficiency of the ore-smelting furnace. The relevance of further development of the ability to control the position of the electrode tip in the OSF space has been confirmed.

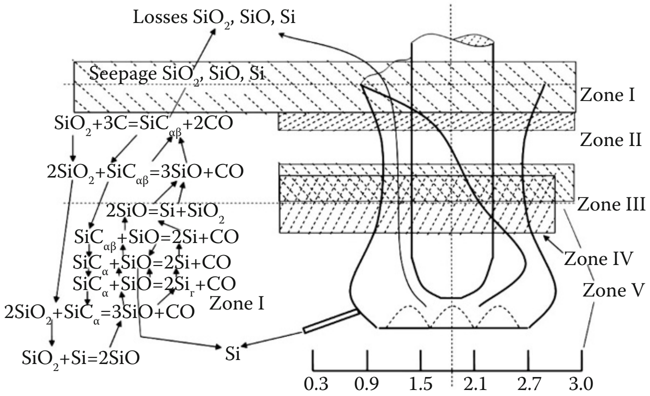
Introduction

A reaction zone represents a heating area for the charge materials, formed around the electrodes in all electric furnaces, and facilitates the release of thermal energy by passing electric current through a resistance and/or by creating an electric arc, change in the aggregate state of the loaded materials, and a complex of chemical reactions that occur within them. Heat generation in this zone, in addition to the electrical into thermal energy conversion, also results from the oxidation of the reducing agent. As the energy content of the technological process increases, the boundaries of the reaction zone become more distinct. The profile of the reaction zone is similar to that of the electrode, but there is a certain degree of distortion due to an uneven distribution of the current density over the electrode surface. The thermal energy density in the reaction zone is non-uniform. The highest density is observed near the electrode, but it rapidly decreases with the distance from the electrode. The temperature variation follows a similar pattern, but is not quite as sharp. In the horizontal section of the bath, the temperature difference is somewhat smoothed out, while in the vertical section, an additional convective heating of the colder charge material takes place using the sensible heat of the reaction gases. Therefore, the heating zone becomes wider than the reaction zone, which is an essential and mandatory condition for the effective performance of the bath, considering high temperature in the reaction zone and heat losses. In metallurgical practice, reaction zones are often referred to as crucibles, which is only true for slag-free processes [1].

Crucibles can be detected after the charge materials have melted, while their contours can be determined during melting based on the charge descent and release of gases. The contours of the crucibles change depending on the degree of preparation of the charge materials, type of reducing agent, power, and electrical conditions [2]. In case of an extended stable operation of the furnace, the wall and bottom of the crucible represent an isothermal surface, the temperature of which theoretically should be close to 1730 °C [3]. The concept of a crucible was introduced by M.S. Maksimenko, who believed that the bottom of the crucible consists of a melt and is separated from the electrode tip by a thin gas-filled layer. The melting product in the form of a so-called "hot heel" accumulates under the magma. According to A.G. Walter, there is a porous mass underneath the bottom of the crucible, which makes it possible for an alloy to seep through [4, 5].

Under the optimal operating conditions of the ore-smelting furnace, the throat of the furnace is sufficiently heated along the entire depth of electrode immersion, the working space is large, and the current distribution in all areas is uniform. As a result, the specific energy consumption decreases by 10% and constitutes about 6.5 MW · h/t [6].

Fig. 1 Technological zones of an ore-smelting furnace [15]



A further increase in voltage and power creates a condition, during which the voltage (being too high) generates higher current in the circuit, causing the controller to start raising the electrode [7, 8]. As a result, a build-up is formed, which complicates the release of the melt. In addition, an increase in heat losses and a decrease in the yield of material occur along with increased entrainment of the charge materials [9, 10]. Depending on the applied voltage, pitcher-shaped crucibles of various heights with or without gas cavities are formed around the electrode. The crucibles were obtained under a constant load of 16 kA. A decrease in electric current results in a narrower cross-section of the reaction zone, while an increase in electric current, on the contrary, makes this zone wider [10–12].

In case of a deviation from the optimal power and technological conditions, when the generation of thermal energy is insufficient, a skulling may occur in the center of the furnace between the electrodes. The size of this region is determined by the degree of deviation from the optimal operating conditions and electrode pitch circle diameter [13]. The charge material located on the surface of the furnace throat is heated to about 500 °C. In addition, there is gas rising from the reaction zone that burns above the throat and provides additional heating. At a small depth below the furnace throat, the temperature of the charge materials is above 1200 °C. This zone contains under-reduced silicon, which undergoes phase transition. The third and fourth zones contain silicon carbide and reduced liquid silicon. Located below these zones is the fifth zone, where electric arcs are burning. In this zone, all components are converted to either a liquid or a gaseous phase. Beneath this zone, on the furnace floor (hearth), a “hot heel” is formed by the liquid melt, which contains silicon carbide and Siloxicon particles undergoing reduction. As a result of burning electric arcs, gases released during chemical reactions pass through all four zones. During the optimal technological regime, the charge material is loose and non-sintered, which ensures high gas permeability and high rate of descent into the sub-electrode space (see Fig. 1). All these zones perform the following two functions: thermal insulation of the reaction zone and aspiration of the fine fractions of the reaction products [14].

Excessive embedment of the electrodes reduces the size of the reaction zone and, hence, increases skulling near the furnace walls and between the electrodes. Such situation may occur, for example, when the reducing agent content in the charge is low. In this case, the majority of the thermal energy is generated directly under the electrode (near the hearth), while the power output in the upper horizons decreases. The cross-section of the reaction zone is significantly reduced, and as a result, the charge descent worsens, leading to a decrease in the silicon yield [16]. Typically, in such cases, the charge in the upper layers becomes sintered or acquires a pasty consistency. As a result, the gas permeability of such material decreases, while the gas pressure in the sub-electrode space increases. This leads to the formation of powerful blowholes and significant entrainment of microsilica along with increased heat losses. Such situation is commonly referred to as excessive quartzitization of the furnace bath [17].

In case of an excessive amount of the reducing agent, the situation is quite opposite. The surface temperature of the furnace throat increases, and a large amount of gases is formed in the furnace. An intensive formation of silicon carbide takes place in the lower layers. It accumulates on the furnace hearth and prevents the melt from exiting the furnace, thus reducing its performance efficiency [18].

An increase in voltage causes the electrodes to be raised, while a reduction in voltage causes the electrodes to be lowered. Thus, the geometry of the reaction zone is uniquely determined by the part of the electrode that is embedded into the charge [19]. Depending on the latter, the distribution of thermal energy in the furnace space varies. The optimal regime can be described as a certain position of the electrodes (current and voltage ratio) with the best use of electrical and thermal powers, while considering the consumption of charge materials and electrical power in relation to the yield of final product (specific productivity) [20]. This position does not depend on the technological process inside the furnace, but is instead determined by the electrical field of the bath.

The size of the cavity can be controlled in two ways: by correct preparation of the charge, which eliminates the presence of fines and foreign inclusions, and by selecting the proper granulation of the reducing agent and quartzite, while reducing the voltage, provided that this will not affect the productivity. In most cases, the second approach proves to be unfeasible. Switching to lower or higher voltages compared to the optimal values that have been established based on long-term practice and observations does not improve the condition of the furnace throat, while the smelting characteristics worsen [21, 22].

Electrode placement

The dimensions of the reaction zones and crucibles depend on the electrode diameters and power. These factors are interrelated and equally affect such dimensions. However, power plays the main role. An electrode serves as a current conductor only in furnaces operating with an open arc. Once submerged into the bath, it becomes the most important structural and technological part of the bath [23]. Electrodes form the reaction zone, and their dimensions determine the size of this zone and the size of the entire bath. Although undesirable, electrodes take part in the reduction of the adjacent layer of ore, leading to electrode burnout. To reduce the latter, the charge always contains a certain excess of the reducing agent, typically up to 10% over the amount required according to stoichiometric calculations [24].

The thermal energy obtained as a result of conversion of the electrical energy is uniquely determined by the values of the electrode current, phase voltage, and $\cos(\varphi)$. The same power can be obtained with different current and voltage ratios, for example, by reducing current and increasing voltage (lower stage of the furnace transformer) or vice versa.

In the former case, conducting a process in such a manner will lead to a low electrode placement and, hence, to overheating of the reaction zone and cooling of the furnace throat, resulting in reduced charge descent and lower performance of the furnace. In the latter case, the electrode will be placed high, leading to a reduced temperature of the melt and increased temperature of the furnace throat [25].

In a furnace operating with submerged electrodes, the electric arc is not visible. The presence of the arcs is detected indirectly, based on electric current oscillograms, readings of the recording devices, furnace humming and the appearance and amount of gases and dust passing through the furnace throat. Many believe that arcs are the essential organic part of the bath and carry the main load. The area under the electrode is considered the place where arcs are burning. According to G.A. Sisoyan, who dedicated a series of monographs to the topic of arc burning in an ore-smelting furnace [26], a powerful arc is formed in the sub-electrode space due to high temperature and intense thermal ionization that occur there: at 30 kA, the arc column can reach 30 to 50 cm in length and up to 30 cm in the cross-section. In his opinion, such arc determines almost the entire energy characteristic of the bath. However, opposing views exist as well [27].

Upon immersion, the side surface of the electrode comes in contact with the lump charge, which ignites a countless number of contact arcs. As a result, charge sintering occurs in the furnace throat, caused by changes in the mechanical properties, and specifically, by softening and melting of silica. The reaction gases formed inside the bath (especially, near the electrode tips) cannot escape fast enough and create an excessive pressure, leading to the formation of gas cavities. Such conditions contribute to the formation of even longer and more powerful arcs. However, even in this case, the arc power constitutes only a very small fraction of the total power of the furnace [28].

According to the experimental results, there is an electric current flowing between the electrode tip and the hearth, which accounts for about one-third of the total bath current during normal immersion. If the power generated in open-arc furnaces during smelting of high-grade ferrochrome fluctuates between 10 and 25%, then perhaps in the furnaces with submerged electrodes, it is significantly lower. Measurements conducted using a three-phase furnace with a capacity of about 7.5 MW for the smelting of 75% ferrosilicon showed that arcs account for about 7–8% of the total power of the furnace [29].

During normal operation of such furnace, the arcs are not visible, and their size cannot be determined. However, considering that all current conductors inside the bath are coupled with strong magnetic fluxes, it is possible to establish the limits that arcs, which are freely burning in the bath, should have. While experiencing the compressive effect of their own inductance fluxes, all current lines in the gas atmosphere should be compressed into a single narrow bundle. The forces compressing the arc bundle are proportional to the square of the electric current, and the pressure acting on the axis of such bundle is measured in kilograms per square centimeter. It is obvious that the arc cannot represent a column measuring 30 cm in the cross-section (at 30 kA). The proximity effect, caused by the mutual inductance fluxes, will result in the deviation of the arcs towards the field with lower magnetic intensity. In a three-phase bath, the arcs will be deflected from a vertical in the direction of the extension of a line passing through the center of the furnace and the electrode [30].

A powerful enclosed arc can be created by raising the voltage without changing the position of the electrodes. But this will immediately have a negative impact on its operation. The bath will emit plumes of white flame and clouds of brown smoke, which are indicative of the burnout of the smelting products. The charge entrainment with gases will sharply increase as well. Ejections of magma and charge, which can be dangerous for the personnel, are also possible. The smelting regime will become abnormal and unacceptable. Despite the increase in power, the technical and economic parameters of the process will worsen.

To date, all ore-smelting furnaces are still considered as part of the family of arc furnaces, which is justified to some extent, since many processes in these furnaces are conducted with open arcs. In essence, furnaces with submerged electrodes are direct resistance furnaces.

Ways to correct deviations from standard operating conditions during the production of metallurgical silicon

Declining technical and economic performance parameters along with worsening working conditions for the service personnel could result from such actions as: non-compliant (out-of-spec) feeding of the charging materials; incorrect granulometric composition; improper treatment of the furnace throat; use of substandard raw materials; operating with "short" or "long" electrodes; deviation from the specified electrical parameters of the furnace. If deviations are detected almost immediately, they can be corrected relatively quickly, but if the furnace operates with these deviations for an extended period of time, they can lead to a profound disruption of the furnace performance, and even to an emergency shutdown [31].

An insufficient amount of the reducing agent in the charge leads to a profound disruption of the technological process, which is characterized by:

- brighter flame at the furnace throat;
- slowed descent of the charge and its sintering at the furnace throat;
- formation of blowholes;
- reduced cross-section of the melting crucibles, with more pronounced boundaries;
- presence of under-reduced quartzite on the electrode tips;
- operation using "long" electrodes;

- fluctuations in electric current values;
- high pressure of gases exiting the taphole;
- violent descent of overheated melt from the furnace;
- reduced (impeded) slag discharge.

Non-conformant granulometric composition of the charge components relative to the specified values results from the fact that the fines of the reducing agent and quartzite contain a large number of impurities, which affect the grade of the final products and the furnace performance. This also affects the gas permeability of the material. Reduction in gas permeability leads to the formation of blowholes due to charge sintering at the furnace throat. A large amount of dust escapes through such blowholes, which reduces the product recovery rate and furnace performance. If the size of quartzite fraction exceeds 100 mm, the rate of silicon reduction decreases. Large-sized quartzite fractions increase the separation of charge components at the furnace throat. An increase in the fractional composition of the reducing agent leads to higher electrical conductivity of the charge. Therefore, the signs of process disruption in case of an increased amount of the reducing agent may be the same as in case of excessively large fragments of the reducing agent, given the specified mass content of the reducing agent in the charge. If deviations in the granulometric composition of the charge are detected, the first thing to do is to bring it back in compliance with the specified values [32].

An excessively high level of the charge in the throat of an ore-smelting furnace constitutes a gross violation of the smelting process management. Such a deviation typically results from:

- an increased amount of reducing agent in the charge;
- operating with the use of “short” electrodes;
- overloading the furnace;
- impeded discharge of smelting products from the furnace.

To eliminate this deviation, it is necessary to first of all eliminate the causes that led to it. In the case of impeded slag discharge, a single load of 20 to 50 kg of limestone into the furnace or adding it to the charge is sometimes used.

Once a deviation is detected during the technological process, the first step is to establish the cause of its occurrence. The inspection stages include the following:

- checking the granulometric composition of the charge components to ensure compliance with the technological guidelines;
- checking for proper functioning of the weighing and feeding systems;
- ensuring the absence of deviations in the charge component ratio;
- checking for the specified positioning of the electrode tips;
- checking the voltage on the high-voltage side of the furnace transformer;
- ensuring systematic and proper maintenance of the furnace throat.

If an insufficient amount of the reducing agent in the charge is detected early, such deviation is corrected by adding 100 to 200 kg of pure reducing agent to the throat of the furnace. Otherwise, the furnace becomes excessively quartzified, leading to a sharp decrease in performance. The latter is characterized by an increased temperature of the melt and a significant decrease in melt output, as well as by practical disruption of slag output and heavy slagging of the taphole. In addition, the automatic protection of the furnace transformer is periodically triggered due to excessive electric current values as a result of significant fluctuations in current load [33]. In this case, to bring the furnace out of such operating mode, it is necessary to ensure the correct operation of the component feeding system and adjust the quartzite-to-reducing agent ratio to match the calculated values, while accounting for the actual moisture content. Upon detecting such malfunctions, it is essential to first of all correct the operation of the feeding system, and then add up to 500 kg of reducing agent to the throat of the furnace. Sometimes, the reducing agent needs to be pushed directly under the electrodes [34].

In the event of a powerful blowhole formation, which could be detrimental to the technological equipment, it must be eliminated by performing a furnace throat treatment. If this is not successful, it becomes necessary to reduce the supplied power (raise the electrodes), and in extreme cases—to kill power to the furnace.

The furnace operation with an excessive amount of the reducing agent is characterized by the following distinctive features:

- high current load due to increased electrical conductivity of the charge;
- high electrode placement (a consequence of the high current load);
- dominating arc mode of electrode operation (a typical humming sound can be heard);
- stable electrode load;
- reduced silicon yield and temperature;
- disrupted slag output;
- a significant amount of gas exiting from the taphole.

The furnace operation with an excessive amount of the reducing agent leads to slag accumulation, reduced performance, and triggering of the system of automatic shutdown of the furnace transformer due to current overload. If such deviation is detected, it is necessary to ensure the correct operation of the feeding system and check to see if the quartzite-to-reducing agent ratio matches the calculated values. If necessary, a batch ratio needs to be adjusted. After that, it is recommended to load several "heavy" batches with an excess of quartzite depending on the degree of deviation from the standard operating conditions. Switching between the stages of the furnace transformer should be avoided. To improve slag output, it is recommended to add up to 20 kg of limestone to the charge per shift [35].

Furnace operation using short electrodes. On the outside, such operation is similar to that in case of an excessive amount of the reducing agent, which is characterized by:

- a typical humming sound of electric arcs;
- fluctuation of current load;
- reduction in the melt temperature and its output;
- a significant amount of gas exiting from the taphole;
- an uneven descent of the charge.

Once such deviation is established, it is necessary to first of all eliminate the cause. Specifically, several electrode slips should be performed in order to lengthen the tips and ensure deep placement of the electrodes at the specified voltage stages.

Now we will review the opposite situation, when a *furnace operates using excessively long electrodes*. The main characteristics of such operation include:

- high and uneven electrode placement;
- triggering of the system of automatic shutdown of the furnace transformer due to current overload;
- decreased rate of charge descent;
- no typical humming sound of the electric arcs with the electrodes being in the upper position, and no charge downslide;
- significant reduction in the melt output due to excessive slagging.

Quite often, such deviation from the standard operating conditions is confused with the case of an excessive amount of the reducing agent, since the main characteristics are similar. Accordingly, the service personnel attempts to feed a "heavy" charge, which will bury the electrodes. As a result, the electrodes become dipped into the slag, the arc mode of operation is lost, and the rate of charge descent drops. To stabilize the furnace operation, it is necessary to raise the electrodes and position them according to the specifications. Therefore, it is important to know not only the location of the reaction zone, but also the location of the actual electrode tips. The disadvantages of operating the furnace using long electrodes include as increased erosion of their lateral surfaces. This also leads to a change in the electrical operating mode and, hence, to a change in the shape of the reaction zone, as well as to a reduction in furnace performance.

Deviation from a specified voltage level on one or several electrodes typically generates voltage imbalance (skew). To eliminate such deviations, it is necessary to stop loading the charge under a specific electrode, and use the manual control mode to start raising the electrode and melt the crucible until the electrode arc is resumed. Once the electrode voltage is reestablished, it is necessary to continue melting the crucible by gradually lowering the electrode. Sometimes, fresh portions of the charge are added under the electrode. Such actions are continued until the electrode phase voltage is restored. Then, the process is continued according to the standard operating conditions.

Build-up formation on the surface of the furnace throat is also considered a deviation from the optimal technological operating mode. Such build-ups are commonly present in the form of overhangs or hanging charge that would not drop. Conducting the process in such a manner can lead to a skull sagging and narrowing of the active zone of the furnace throat, since there is not charge descent in these areas. The build-up formation in the taphole area particularly reduces the furnace performance. To mitigate such deviation, the following steps should be followed:

- check the accuracy of the charge feeding system;
- check the charge component ratio, while accounting for the actual moisture content;
- check the frequency of charge loading;
- check the correctness of the furnace throat treatment by the service personnel;
- check the granulometric composition of all charge components;
- check the position of the electrode tips and their configuration;
- compare the electrode pitch circle diameter with the furnace specifications;
- knock down formed build-ups and load fresh portions of the charge materials along with pure quartzite (up to 1200 kg). After quartzite has melted, load 200 kg of charcoal into the furnace throat.

The length of the electrode section from the lower edge of the contact plates to the charge surface should be minimized (200 to 400 mm in a normally operating furnace). As an exception (when using long electrodes and changing the smelting shape of the furnace), a reverse electrode slipping is performed.

Analysis of common errors

Common errors, leading to reduced performance of the furnace and the quality of metallurgical silicon, can be divided into the following groups:

- Charge composition: incorrect quartzite-to-reducing agent ratio (improper operation of the weighing and feeding system), non-conformance of the granulometric composition.
- Incorrect positioning of the electrode tips: operating with either “short” or “long” electrodes.
- Improper treatment of the furnace throat (operator errors when operating charge breaking and loading machines).

The first group of errors primarily leads to a decrease in product yield and a reduction in the quality of silicon due to an excess or lack of reducing agent. This primarily affects the size of the reaction zone and the completeness of the silicon reduction process. Such problems are addressed by implementing a process for monitoring the supplied quantities of quartzite, bituminous coal, charcoal, and petroleum coke, as well as by accounting for the moisture content of the coal, and by ensuring the proper operation of the component feeding system. Industrial plants utilize special batch-weighing feeders. Such feeders account for the mass (not volume) of charcoal, since its moisture content will be different immediately after production and delivery, and after some time. This is due to the fact that charcoal has excellent absorption properties and will absorb moisture from the atmospheric air. This leads to a feeding system error.

The second group of errors is associated with the operation of the system that controls electric current in the "short" (high-current) circuit. The electrode positioning system contains a current control loop that adjusts electric current based on the position of the electrode: the higher the electrode, the lower the current and vice versa. Under the standard operating conditions, the electrode occupies the optimal position within the furnace space. However, if the electrode is raised, the current in the "short" circuit will decrease, and if the electrode is lowered, the current will increase (without switching stages of the furnace transformer). In this case, due to a decrease in the surface area and an increase in the electric arc resistance, the power output will decrease. When loading the ore-smelting furnace with a charge containing an excessive amount of the reducing agent (which has low resistance), the current will increase, and the controller will issue a command to raise the electrodes, which will result in shifting of the reaction zone. In case of an insufficient content of the reducing agent, the opposite situation will occur. By eliminating the possibility of errors from the first group, the likelihood of errors associated with the positioning of the electrode tips will be significantly reduced.

The third group of errors can be attributed to a so-called "human" factor, since the charge loading and furnace throat treatment operations are performed without the use of any automation, while relying solely on mechanization. The quality of the furnace throat treatment depends on the operator's professionalism and experience. Operators visually determine the height of the charge cone near the electrode. Such errors occur less frequently than those from the first two groups, and they can only be eliminated by implementing a meticulous control by the foremen and engineering personnel.

Planned scientific and technical tasks

The relevant tasks include studies of the additional parameters, characterizing the OSF condition (including electrical, technological, and thermal), and their implementation into a control system. It is planned to conduct further development and implementation of a system for determining the position of the electrode tip and the electrode consumption rate. This will enable obtaining a real-time information about the electrode breakage and increased electrode burnout, as well as the location of the electrode tip and, hence, the reaction zone. In addition, this will help to solve problems concerning symmetrical positioning of the electrodes in the furnace.

Conclusion

The paper discusses the specifics of operating ore-smelting furnaces (OSF) during a carbothermic reduction of silicon. Specific types of deviations from the standard operating conditions include:

- operation using short electrodes (main signs—decreased melt temperature, fluctuation of current load, and distinctive humming sound from the electric arcs);
- operation using long electrodes (main signs—reduced melt output due to a significant amount of accompanying slag, decreased charge descent rate, and high current load);
- insufficient content of reducing agent in the charge mix (leads to a severe disruption of the OSF operation, formation of blowholes, unstable current load, melt overheating, decreased cross-section of the crucibles, and reduced charge descent);
- excessive content of the reducing agent in the charge mix (resulting high current load leads to high electrode positioning, switching to arc operation mode, and reduction in silicon yield and temperature);
- electrode voltage imbalance (causes a voltage imbalance (skew) in the "short" (high-current) circuit and a sharp drop in the furnace performance);

- build-up formation (causes narrowing of the active zone of the furnace throat, skull sagging, and increased heat losses);
- non-conformance of granulometric composition (a large amount of fines causes a reduction in gas permeability of the charge along with sintering of the furnace throat; blowholes are formed; large fragments of the reducing agent cause a decrease the silicon reduction rate and an increased current load at a proper quartzite-to-reducing agent ratio in the charge mix);
- operation with an excessively high furnace throat (results from improper treatment of the furnace throat, excessive amount of the reducing agent, and excessive furnace loading).

The reaction zone is the area around the electrode tip, where thermal energy is released either from a resistance, or an electric arc, and is used to support a complex of chemical reactions. To operate according to the technological guidelines, it is necessary to maintain both the electrical parameters and the quartzite-to-reducing agent ratio in the charge mix. The location and size of the reaction zone determine the furnace performance and the quality of the reduced silicon. Therefore, these two operating parameters of any ore-smelting furnace are extremely important, which makes their control a relevant task.

All deviations were subdivided into three groups based on the cause of their occurrence, and corresponding conclusions have been made about possible ways to eliminate such deviations.

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