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# IMPROVING THE EFFICIENCY OF THE FERROALLOY SMELTING PROCESS IN ELECTRIC ARC FURNACES BY IMPROVING CONTROL AND MANAGEMENT OF TECHNOLOGICAL MODES

**Abstract.** *The article addresses the issues of improving the efficiency of ferroalloy smelting in electric arc furnaces by enhancing the control and management of technological regimes. Recent global trends, such as the increase in the production of high-quality alloy steels and semiconductor products, have led to a sharp rise in the demand for ferroalloys and crystalline silicon. In this context, the intensification of technological processes and the optimization of energy consumption in ferroalloy electric furnaces have become particularly relevant.*

*The ferroalloy smelting process is based on the carbothermic reduction of metals from their oxides, occurring at high temperatures with significant heat absorption. Although the mechanisms and kinetics of the main reduction reactions have been well studied, in industrial conditions, the techno-economic indicators of the process are significantly inferior to those achieved in laboratory settings. The extraction rate of target elements decreases to 75–80%, and the energy consumption exceeds the theoretically necessary amount by 1.5–2 times.*

*Traditional approaches to improving the ferroalloy smelting process through the enhancement of furnace designs and the selection of charge materials with specific physico-chemical properties have largely exhausted their potential. In the context of continuously rising energy costs and deteriorating raw material quality, the urgent problem now lies in implementing fundamentally new approaches to technological process control, focused on detailed monitoring and analysis of the furnace's current state.*

*The authors justify the necessity of transitioning from the "input-output" control system to a more advanced "input-state-output" principle, which enables real-time analysis of the furnace workspace parameters and prompt influence on the course of the*




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*technological process. In particular, significant attention is devoted to the development of methods for analyzing the electrical, thermal, and physico-chemical characteristics of the active zone of the furnace, which determine the main transformation processes of the charge.*

*The paper discusses the design features of electric arc furnaces and describes the structure of the workspace for different types of processes - slag-free and slag-forming. It is shown that the distribution of energy among the zones of the charge, the arc, and the melt has a substantial impact on the techno-economic indicators of production. The peculiarities of arc burning, heat transfer processes, and ionization in the gas cavities of the furnaces are studied.*

*The article highlights the main methods for investigating processes in furnaces: probing, analyzing oscillograms of current and voltage, determining the resistances of the charge and melt, as well as modern methods for assessing power distribution across furnace zones based on measurements of electrical parameters. Special attention is paid to the problem of increasing the accuracy of assessing the parameters of energy processes without interfering with the technological process.*

*The authors emphasize the importance of optimizing the modes of electric power supply and the structural parameters of furnaces to ensure the stability of the bath operation, reduce the dispersion of fluctuations, and minimize losses. Methods for selecting optimal electrode immersion parameters, managing charge regimes, and selecting charge materials considering their electrophysical properties are presented.*

*The article makes a significant contribution to the creation of a scientific basis for improving the efficiency of ferroalloy smelting, which is of particular importance in the context of the modern energy crisis and the growing demands for the quality of metallurgical industry products.*

**Keywords:** *ferroalloy smelting; electric arc furnace; carbothermic reduction; automated control; techno-economic indicators; energy distribution; electric arc discharge; process optimization; charge materials; energy consumption; furnace state control.*

## Introduction

The global trend towards increasing the production of high-quality alloy steels and semiconductors, which has emerged in recent years, has defined the growing demand for ferroalloy and crystalline silicon smelting. Mass production ferroalloys are obtained in electric arc furnaces by a carbothermic method based on the reduction of metals from their oxides. The key feature of this method is that the reactions between oxides and carbon occur at high temperatures with significant heat absorption. The specific energy consumption during the production of different alloys ranges from 3 to 18 MWh per ton. The mechanisms and kinetics of the reduction reactions are fairly well studied, and the conditions for their optimal progress have been determined and optimized. However, while in laboratory conditions one of the main indicators of the process - the extraction rate of the target element - reaches 90% or higher, during industrial implementation, it is significantly lower, around 75–80%, and the specific energy consumption exceeds the theoretical minimum by 1.5 to 2 times.

Numerous research efforts aimed at improving furnace designs and selecting charge materials with specified physico-chemical properties have helped reduce the gap between theoretical and actual process performance. However, this reserve is now almost exhausted. In conditions of high energy costs and the tendency for further price increases, the share of energy expenses in the production cost structure is growing substantially. Furthermore, the declining quality of ores and carbonaceous reductants leads to a significant deterioration in the techno-economic indicators of production. Therefore, the issues of intensifying technological processes and improving production efficiency are becoming particularly urgent.

A specific feature of ferroalloy technologies is the inaccessibility of the furnace workspace for direct measurements, resulting in a lack of real-time information about the process state, which has historically determined the widespread use of the "input-output" control principle. However, the complex interrelation of chemical, electrical, and thermal processes in the furnace bath requires a different management approach - the "input-state-output" principle.

The technical re-equipment of the ferroalloy industry, which began at the end of the 1970s, led to an increase in the power capacity of existing furnaces and the commissioning of units with installed capacities up to 81 MVA. As a result, the management of these facilities has become significantly more complicated, necessitating a scientifically based study of the full diversity of processes occurring in the furnace bath and their interrelationships. At that time, the level of monitoring of key technological parameters was extremely low, and the underdevelopment of


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methodological frameworks for process state analysis led to an inefficient, largely intuitive approach to process control. The use of automated systems for these purposes was limited by the low capabilities of domestic computing technology.

The significant progress in computing technology that began in the 1990s greatly improved the quality of process monitoring and control. This allowed the development of local automated control systems that included automatic regulators for electrical regime parameters. With the development of network technologies, it became possible to create large databases that integrate technological and economic process parameters along with tools for their timely updating and processing. However, the methodological basis of such systems has not undergone significant changes, and most of them still operate according to the "input-output" principle. Therefore, special attention must be given to the development of methods for monitoring and analyzing the process state when designing control systems.

The ferroalloy furnace, as a control object, represents a complex dynamic system. The interconnection of physico-chemical, thermal, and electrophysical processes occurring in the furnace bath, as well as their different inertia, determine their stochastic nature. Insufficient information about the process state leads to untimely or often incorrect application of control actions. The result is a fluctuating process behavior characterized by the alternation of transitions from one inefficient state to another. The higher the furnace capacity - and thus the longer the transient processes - the greater the dispersion of these fluctuations, and the higher the material and energy losses accompanying the process.

Another negative consequence of insufficient informational support for process control is the largely subjective nature of decision-making. Responsibility for applying the necessary control actions generally falls on the furnace operator. Thus, the quality of process control becomes dependent on the technical training and experience of the personnel, meaning that the control procedure is not formalized and is often performed intuitively. Consequently, the probability of errors during control execution is very high. Formalizing the control procedure means defining and clearly understanding the sequence of steps needed to achieve the desired state of the object, offering a single, reliable way to lead the process toward optimal operation.

Expanding the information base by introducing additional parameters that describe the process state allows for a quantitative analysis of the technological parameters' interrelations and the development of methods for regulating the main technological regimes.

The objective of this research is to develop scientifically grounded methods for real-time control of the ferroalloy smelting process in electric arc furnaces, to improve the regulation of technological regimes, and to optimize the distribution of energy parameters within the furnace workspace. Achieving these goals is expected to ensure the intensification of the smelting process, improvement of the techno-economic performance of production, reduction of energy consumption and material losses, and create the foundation for implementing modern automated control systems for ferroalloy smelting processes under conditions of limited informational support and high complexity of the physico-chemical interactions.

**Presentation of the Main Material**

Electric arc reduction furnaces intended for the production of ferroalloys are continuous operation units, as these technologies are characterized by continuous charging, processing of charge materials, and periodic tapping of slag and metal. The electrical circuit of the furnace includes the furnace transformer, the secondary current supply system (short network), self-baking electrodes, and the melting bath. A distinctive feature of the carbothermic reduction of metals in electric arc furnaces lies in the direct conversion of supplied electrical energy into heat within the working material itself, that is, on the active resistances of individual zones of the furnace workspace: in the charge, the melt, and the arc discharge. In turn, the resistances of these zones depend on a multitude of factors determined by the electrical, thermophysical, and physico-chemical processes occurring in the furnace bath and the properties of the materials involved. Given that these processes are closely interconnected, the interdependence of the parameters of the main technological regimes - electrode, electrical, and charge regimes - is highly complex.

At the same time, studying the interrelation of energy and technological process parameters is critically important for solving the problems of intensifying the operation of electric arc reduction furnaces, optimizing technological regimes,


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and developing production control systems. It is worth noting that at the early stages of electric furnace technology development, arc reduction furnaces were primarily viewed as electrical devices, with less attention paid to the study of physico-chemical and thermophysical processes. The first works on studying the relationship between energy parameters and technological aspects were conducted by one of the founders of domestic electric furnace technology, M.S. Maksimenko [1]. He was the first to point out that achieving high techno-economic production indicators requires the optimization of the energy characteristics of the process. According to M.S. Maksimenko, these characteristics include the volumetric densities of energy and power released in solid and liquid conductors as well as in the gas discharge.

Subsequently, this research direction was further developed in the works of A.S. Mikulinsky, Ya.S. Shchedrovitsky, S.I. Khitrik, S.I. Telnoy, and other scholars. A.S. Mikulinsky can be considered the founder of the comprehensive approach to studying processes in the baths of ore-reducing electric furnaces. He outlined the main directions in the theory and practice of ore electric furnace technology and proposed the classification of electric furnace processes based on the quantity of slag produced [2]. According to this classification, slag-free processes are those in which the slag ratio (the mass of slag relative to the mass of metal) is insignificant, approximately ~0.03–0.05, because practically all elements present in the ore are reduced. This group includes the processes of producing silicon and high-silicon ferroalloys.

Slag-forming processes correspond to selective reduction technologies, where only a group of target elements present in the ore is reduced, while oxides of other elements form the slag. These processes include the production of ferrosilicomanganese (slag ratio 0.45–0.6), ferromanganese (0.8–1.2), and carbon ferrochrome (0.8–0.9). Some specific features differentiate the processes of the first and second groups. Thus, for slag-free processes, a powerful, stable arc discharge is characteristic, shielded by the charge and shunted by its resistance. In slag-forming processes, a powerful arc only exists during the tapping of the melt from the furnace and for a short period afterward. The electrical resistance of the charge in slag-forming processes is significantly higher than in slag-free ones, as less carbonaceous reductant is required for selective reduction, and carbon has the highest conductivity among all charge components.

According to the classification proposed by B.M. Strunsky [3], reduction processes in electric arc furnaces are distinguished by the methods of energy release in the working space, highlighting the following main groups:

- In the near-electrode zone and under-electrode gas cavity covered with charge materials;
- In the slag;
- Through open arcs on the burden surface (typically for refining processes).

The complex nature of the interrelation between energy and technological parameters, as well as the mutual influence of individual technological regimes, defines the multifaceted variety of studies of electric arc furnace processes as objects of control.

Among the main research directions, the following can be distinguished:

- Investigation of the kinetics and mechanisms of carbothermic metal reduction reactions;
- Study of the structure of furnace bath workspaces;
- Experimental research and mathematical modeling of electrical and temperature fields in the furnace bath;
- Study of the physico-chemical, thermophysical, and electrical properties of workspace materials;
- Examination of the distribution of energy across different zones of the workspace and the development of methods and algorithms for process optimization;
- Development and implementation of automated control systems for the technology.

The advancement of understanding regarding the structure of the furnace workspace for carbothermic reduction enables a deeper comprehension of the kinetics and mechanisms of the processes and the specifics of energy supply to individual charge transformation zones. This knowledge is also necessary for furnace


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design, creation of mathematical models of the process and individual technological regimes, and the development of control and optimization algorithms.

The structure of the furnace bath workspace is predominantly determined by the horizontal distribution of materials: raw charge, intermediate products, the target alloy, and slag. The first studies [4] examining the structure of the workspace were conducted by disassembling cooled furnaces used for the smelting of carbon ferrochrome, ferrosilicomanganese, and ferrosilicon. However, the assumption underlying these studies-that the structure of the cooled furnace corresponds exactly to that of an operating furnace-was not fully confirmed in practice. Nevertheless, data obtained from the disassembly of cooled furnace baths allow for qualitative conclusions about the relationships between the materials and products of smelting.

Notably, it was observed that there is no clear layered separation between the solid charge, magmatic mass, slag, and metal inside the furnace. The boundaries between these phases have complex configurations and are characterized by mutual penetration. Significant advances in studying the active zones of operating furnaces were made by I.T. Zherdev and his collaborators through the use of probing methods [5]. Their work confirmed the existence of gas cavities, estimated their dimensions, and determined the transition boundaries where the charge materials change from one physical state to another, as well as the configurations of electrical and temperature fields.

Important observations for the theory and practice of electric furnace processes were also made by Japanese researchers T. Otani and M. Saito. Using a graphite tube equipped with an optical system and gas sampling apparatus, they probed the gas cavity of a 2.8 MW silicon smelting furnace. Through this system, they were able to determine the temperature of specific zones of the electrode and crucible, and to observe the conditions and transformations of materials on the cavity walls. Their studies confirmed the existence of the gas cavity and expanded the knowledge about its structure.

A summary of data on furnace bath structure is presented in works [2, 3]. For slag-free processes, the structure of the furnace workspace appears as follows: above the gas cavity surrounding the electrode tip lies a layer of solid charge, typically conical in shape at the burden surface, composed of quartzite, carbonaceous materials, and metallic additives. The lower portion of the burden surface, which covers the gas cavity from above, forms a dome consisting of a viscous silicon dioxide melt interspersed with pieces of carbonaceous reductant, on the surfaces of which silicon carbide forms. The concentration of silicon carbide increases with the depth of immersion.

The walls of the gas cavity mainly consist of silicon carbide and siliceous slag with inclusions of the alloy. The target product, silicon alloy, coagulates into large droplets that drain to the bottom of the cavity and fill the channels in the porous mass of the "false" furnace bottom, which is primarily composed of silicon carbide and slag magma. Due to the continuous interaction between silicon monoxide and silicon carbide, the charge at the cavity walls is constantly renewed while maintaining the relative shape and size of the cavity.

In furnaces operating slag-forming processes, the structure of the workspace is described less extensively in the literature. Due to the periodic tapping of the alloy and slag, the structure of the active zone changes throughout each smelting cycle. According to most researchers [6], a viscous, slag-saturated layer of metal forms at the furnace bottom, atop which accumulates a pool of metal melt that periodically taps out and covers the entire area confined by the furnace lining. Above the metal melt lies a slag layer of variable thickness. Depending on many factors, the slag layer may occupy part or all of the bath surface during the smelting cycle. Between the solid charge and the slag is a layer of magmatic charge. The highest concentration of target elements is found at the slag–magmatic boundary. This description mainly applies to furnaces used for smelting carbon ferrochrome and ferromanganese.

Some differences are observed in the structure of furnace baths used for the production of ferrosilicomanganese and one-stage silicochromium. These furnaces are characterized by more developed gas cavities and a non-uniform cross-sectional distribution of the slag melt. Differences also exist in bath structure between furnaces producing manganese-based and chromium-based alloys.

For example, during ferrosilicomanganese production, a wide coke layer (the coke burden) lies above the slag. The heating of this coke layer induces the melting of the ore component of the charge and filtration of the primary melt


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through it. In furnaces smelting carbon ferrochrome, the ore layer is more developed and consists of semi-molten pieces of ore, slag, and coke. Droplets of carbon ferrochrome, formed in the solid-phase reduction zone, pass through this layer and are refined by carbon.

An important element of the furnace workspace is the electrodes. During the smelting process, they are gradually consumed due to interactions with the oxides of the charge, the exhaust gases, carbon sublimation from the arc spot, and thermal destruction. Therefore, the electrodes must be periodically lengthened. In ferroalloy smelting, self-baking electrodes are commonly used, while in silicon production, graphitized electrodes are preferred.

The most widely adopted in ferroalloy technology are cylindrical self-baking electrodes with diameters ranging from 100 to 200 cm, lengths between 15 and 20 meters, and weights of 15–30 tons. The steel casing, reinforced with radially arranged stiffeners, is filled with electrode mass, primarily composed of thermoanthracite (50–70%), along with foundry coke, graphitized coke, and production waste from the electrode industry. The binding material is coal tar pitch (25–28%).

The depth of electrode immersion into the charge determines the position of the reaction (active) zone within the furnace workspace. The correct selection of immersion depth significantly influences the techno-economic indicators of the process. The contact area between the electrode and the charge - and hence its diameter - greatly affects both the active resistance of the bath and the distribution of energy across the workspace zones. Additionally, electrode movement is the most frequently employed control action during the smelting process. Therefore, studying the properties of electrode mass, the design features, and operating modes of electrodes is of particular importance for solving technological control tasks.

The most comprehensive information on this topic is provided in the monograph by M.I. Gasyk [7]. The purpose of self-baking electrodes is to deliver electrical energy directly to the zones where material transformations occur. Moreover, the electrode acts as a regulator of electrical resistance and the position of the active (reaction) zone within the furnace workspace. Its carbon also plays the role of a compensator for the shortage of reductant in the charge.

Research [7] established that the sintering process proceeds in three stages: heating and melting of the electrode mass, coking, and graphitization of the coked electrode section. This sintering is primarily ensured by Joule heating within the electrode, although this heat constitutes no more than 10% of the electrode's total energy balance.

According to [7], several factors significantly influence the baking process: the current load, the height of the liquid electrode mass column, the air temperature at the exit of the "electrode-mantel" space, the parameters of the cooling water, and the overall progress of the technological process. To implement a rational coking regime, it is necessary to match the electrode baking speed to its consumption rate, which requires proper selection of the current load and the electrode slip rate. Naturally, the optimal solution to this problem can be achieved only through the application of automated monitoring and control systems [8].

The increase in installed furnace capacities to 63–80 MVA and the corresponding rise in current strength to 180–200 kA necessitated the use of larger-diameter electrodes (up to 2200 mm) and rectangular-section electrodes. As a result, due to the development of their lateral surface, the resistance decreased, leading to a drop in the power factor - the ratio of the active resistance component to the furnace impedance. Furthermore, the increase in electrode diameter led to a redistribution of energy across the furnace workspace zones because the increased ratio of "delta" to "star" currents caused a higher proportion of energy to be released in the charge.

An important feature of electrodes, as conductors of alternating electric current, is the non-uniform distribution of current density across their cross-section due to the "skin effect." Since the penetration depth of the electromagnetic wave into the electrode does not depend on its size, the main portion of the electrical power is released within a zone of equal width for both large and small diameter electrodes. Consequently, with approximately equal volumetric power densities in the carbon part of the electrodes, the ratio of heat-releasing to heat-absorbing volumes of the electrode mass is significantly lower for larger electrodes than for smaller ones. Therefore, the baked portion of large-diameter electrodes exhibits low thermal stability. Other issues arising during electrode operation are discussed in [8].


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A particularly important zone of the furnace workspace, in terms of heat exchange intensity and energy concentration, is the gas cavity containing the electric arc. The arc - one of the many types of electrical discharges in gases - represents a column of plasma moving within an electromagnetic field and serves as a highly efficient converter of electrical energy into thermal energy.

The theory of low-temperature (thermal) plasma and electric arc discharge has been extensively developed and presents no major contradictions. Key contributions to this field include the monographs by A. Engel and M. Steenbeck, W. Finkelnburg and G. Meckel, N.A. Kaptsov, D.M. Somerville, and other researchers. Here, we shall highlight only the fundamental principles of this theory as they pertain to powerful (current above 50 A), compressed arcs.

The compressed electric arc, due to its high current density and constriction, achieves very high temperatures in its core, often exceeding several thousand degrees Celsius. The surrounding plasma envelope enables efficient transfer of heat to the surrounding materials - the charge, the slag, and the electrode surfaces. Due to these characteristics, the arc plays a pivotal role in providing the necessary thermal energy for driving the reduction reactions and phase transformations within the furnace bath.

The stability and characteristics of the arc depend heavily on several factors, including the composition and pressure of the gas atmosphere, the electrical parameters of the circuit (current and voltage), the configuration and condition of the electrodes, and the characteristics of the furnace charge. Variations in these factors can lead to changes in the arc length, temperature distribution, and energy density, all of which significantly influence the efficiency and stability of the smelting process.

In the context of ferroalloy production, understanding and controlling the behavior of the arc is crucial for optimizing energy use, minimizing electrode consumption, and ensuring the desired quality of the final alloy product. Research into arc behavior and its interaction with the furnace materials remains an important area of study, as it directly impacts the overall techno-economic performance of the electric arc furnace operations.

The electric arc tends to stabilize itself in such a way that its consumed energy is minimized (Steenbeck's principle of minimum energy).

The temperature of the arc column is directly proportional to the ionization potential of the gas.

The cathode current is primarily governed by thermoelectronic emission, with a lesser role played by autoelectronic emission.

The plasma conductivity is proportional to the density and mobility of electrons.

The degree of ionization ($\chi$), defined as the ratio of the number of ionized molecules to the total number of molecules before ionization, considering the quantum statistical weights of the molecular (gg) and ionic (gp) states formed, is determined by the Saha equation.

Most of the voltage drop across the arc occurs in the near-electrode regions of the gas discharge gap, with the anode voltage drop being significantly higher than the cathode drop.

The static current-voltage characteristics (CVC) of the arc show a decreasing trend.

In his work, G.A. Sisoyan [9] proposed classifying powerful AC electric furnace arcs based on their thermal state and heat exchange regime with the surrounding environment. According to this classification, all arcs are divided into three groups. As the author notes, the external manifestation of the arc burning behavior can be observed in the forms of the current and voltage curves.

The first group includes arcs with an intensely cooled arc column. Due to the intense cooling, the discharge gap rapidly deionizes during the current decay, and the arc extinguishes before the voltage curve crosses the zero point. The voltage at which the arc extinguishes - the extinction voltage - can create a potential gradient necessary to sustain the current. During the period when the arc is extinguished, the deionization of the medium increases, requiring a higher voltage for re-ignition compared to the voltage at extinction. Hence, ignition and extinction peaks are observed on voltage oscillograms, where the ignition peak corresponds to a higher voltage value, and the arc current curve shows pauses. Arcs of this group are typically observed in electric steelmaking furnaces.

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The second group consists of arcs with a moderate degree of column cooling, burning under more favorable thermal conditions. In this case, the ignition and extinction peaks on the voltage oscillograms are much smaller or may even be absent. The voltage curves during burning do not exhibit convexity and have a trapezoidal shape. Pauses in the current oscillogram still exist but are significantly shorter. This group includes arcs burning in enclosed volumes under less favorable thermal and technological conditions, such as after furnace downtime.

The third group includes arcs with minimal column cooling, burning steadily and continuously. The deionization of the arc column occurs so slowly that by the end of the current half-cycle, a sufficient number of charged particles remain in the discharge gap to sustain the current. According to the author, if the applied voltage at that moment is sufficient to overcome the cathode and anode potential drops, the next current period begins without a pause, and the arc burns continuously, with the current curve having a sinusoidal shape when powered by a sinusoidal voltage source. This type includes powerful arcs shunted and shielded by the burden, burning in ore-smelting furnaces intended for the production of ferroalloys, such as ferrosilicon of various grades and crystalline silicon.

An effective method for studying the electrical parameters of the arc discharge is the oscillographic recording of current and voltage curves, as well as the registration of static and dynamic current-voltage characteristics (CVCs). Static CVCs of the arc represent the relationship between the root mean square (RMS) values of the arc voltage drop and the arc current at a given arc length, while dynamic CVCs describe the relationship between the instantaneous values of these parameters.

In one of his early works [10], S.I. Telny, analyzing the results of oscillograms of arc voltage in electric furnaces, concluded that the arc voltage remains constant throughout the burning period. Based on this conclusion, he derived the equations for current and voltage curves. In a subsequent work, together with I.T. Zherdev [11], he published oscillograms of the current and voltage of arcs burning in single- and three-phase furnaces and confirmed the assumption of the constancy of the arc voltage and the presence of pauses on the current oscillograms.

Similar conclusions were reached by foreign researchers studying the characteristics of powerful (current strength from 10 to 50 kA) electric arcs under various heat exchange conditions with the surrounding environment. They noted the presence of ignition and extinction peaks on the arc voltage oscillograms under conditions of intensive cooling, the reduction of these peaks under moderate cooling of the arc column, and their disappearance under conditions of high thermal insulation.

The linear parameters of the circuit also have a significant impact on the arc characteristics, namely: resistances shunting the arc and resistances connected in series with it, as well as the circuit inductance. In works [11, 12], an analysis of the influence of these factors on arc burning modes was conducted. In particular, it was noted that the series resistance serves both as a limiter of the arc discharge current and stabilizes the arc burning mode. The series-connected inductance, under certain conditions, ensures a continuous arc burning mode, eliminating current pauses and giving the voltage a rectangular waveform.

The distinct difference between the arc current and voltage curves from a sinusoidal form unambiguously indicates the nonlinear nature of the arc’s electrical properties. However, some researchers, including G.A. Sisoyan [9] and P.V. Sergeev [13], based on oscillographic analysis of currents and voltages in industrial furnaces, argued that with increasing temperature, the arc increasingly exhibits the properties of an active conductor with a linear CVC.

It is evident, however, that such mistakes arise from neglecting the voltage drop across the melt resistance. When added to the trapezoidal arc voltage signal, it yields a curve close to a sinusoid, which leads to incorrect conclusions.

A significant contribution to the development of the theory of the shunted three-phase electric arc was made by I.T. Zherdev. In his works [14, 15], he provided solutions to systems of differential equations describing the balance of voltages in individual phases and branches of the equivalent electrical circuit of a ferroalloy furnace. His models assumed equal active and reactive resistances in each phase, constant and equal arc voltages across all three phases.

The outcome included formulas for calculating the time dependencies of arc and burden currents, phase voltage drops, voltage drops across the charge, and


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neutral point shifts. Among the main results of these studies are the conclusions that:

- The convex form of the phase voltage drop curve does not contradict the assumption of constant arc voltage;
- The melt resistance plays an exceptional role in regulating the electrical regime;
- A continuous current (without pauses) mode of burning a shunted arc is impossible.

Thus, it becomes evident that the idealized dynamic CVC of an AC arc has the so-called "relay form." Numerous studies have confirmed that the static CVCs of powerful arcs exhibit a falling characteristic. Some researchers also noted that for current densities exceeding critical values - where the volume power density of the arc discharge becomes sufficient to cause intensive electrode material erosion - an ascending section appears on the static CVC.

The final confirmation regarding the forms of current and voltage curves of powerful shielded and shunted arcs and their dynamic CVC was provided in work [16] by Ya.B. Dantsis. For this study, an original probing method was applied: a probe was introduced at a constant speed through an axial hole in the electrode. As the probe moved, the voltage between the electrode tip and individual points within the gas discharge gap was oscillographically recorded. The results of these investigations, conducted on a 1 MVA single-phase industrial furnace, fully confirmed the assumptions of S.I. Telny and I.T. Zherdev.

Being a conductive medium and thus an element of the equivalent electrical circuit of the furnace workspace, the melt zone significantly influences the energy characteristics of the process. In particular, it affects the power distribution across the bath zones, the configuration of the temperature and electrical fields, and, consequently, the main techno-economic performance indicators of the process.

The structure of this zone differs substantially between slag and slagless processes. In slagless processes, the so-called "false bottom," which consists of an oxide-carbide layer, forms due to local, and sometimes systematic, deviations of the charge composition from stoichiometry. It has a porous structure and is impregnated with a liquid metal melt. Since the constituent materials of the false bottom have a higher specific electrical resistance compared to ferroalloys and silicon, during metal tapping, as the pores of the charge materials are emptied, the resistance of the melt zone increases.

The slag ratio in the technologies for producing crystalline silicon and silicon-rich ferroalloys is very low (approximately 0.03–0.05). However, the specific resistance of slag exceeds that of the metallic melt by a factor of $10^2$–$10^3$. Therefore, the assertions made by some authors about the negligible influence of slag resistance on practical calculations of electrical parameters are incorrect.

In work [17], a generalization of data regarding the viscosity and melting temperatures of slags formed during ferroalloy smelting was conducted. It was noted that during ferrosilicon production, an increase in silicon content results in a higher proportion of silica in the slag and a slight increase in its melting temperature. In slag processes, the slag occupies the predominant volume of the melt zone. Possessing the highest resistance compared to other zones of the workspace and being the major consumer of thermal and electrical energy, it largely determines the character of the temperature and electrical regimes of the smelting process.

The electrical circuit of reduction furnaces can be represented as an equivalent circuit model with lumped parameters. This simplification is particularly important for solving tasks related to the real-time control and management of the electrical regime. Equivalent circuits for the useful load - essentially the furnace workspace - differ between slag and slagless processes and are determined based on the current flow patterns obtained from research data.

For slagless processes, the substitution circuit of one phase of the load consists of the arc resistance (a nonlinear element) and the melt resistance (Rp) connected in series, shunted by the charge resistance (Rch). This circuit is further connected in series with an inductive reactance, determined by the sum of the inductances of the open electrode segment and the furnace bath, along with the mutual inductances between the electrodes of different phases.

In slag processes, the arc is shunted by the charge resistance, and the melt resistance is connected in series with them.

The difficulty in assessing the energy distribution among the zones of the workspace primarily stems from the lack of sufficient information about the


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electrical parameters of the substitution scheme. Indeed, the only directly measurable electrical characteristics are the currents in the electrodes and the phase voltage drops, which are insufficient to calculate the resistances and the power dissipated in individual zones.

Therefore, certain studies focusing on the distribution of potential and current density within the ferroalloy furnace baths, conducted via probing methods, are of significant interest. For example, in work [18], it was shown that in a 10 MVA furnace smelting silicochromium, the current density in the charge increased with depth (from 5 to 50 cm) from 0.2 to 0.8 A/cm², the specific resistance decreased to 0.48 Ω·cm, and the volumetric power density increased to 0.5–0.6 W/cm².

I.T. Zherdev and his colleagues [19] demonstrated that in furnaces smelting silicon-rich alloys, the current density in the charge varied between 0.45 and 0.76 A/cm² at depths ranging from 20 to 40 cm.

To determine the charge resistance and the combined resistance of the arc and melt, V.P. Vorobyov [20] proposed a method based on the simultaneous measurement of electrode currents and useful phase voltage drops as the electrodes are lifted by certain distances from their normal immersion level. From the measured currents and voltages, the average phase bath resistance was calculated. On the characteristic curve of resistance change during the electrode lift above 70–80 cm from the nominal immersion, constant resistance sections were noted, which were then considered as the average resistance of the charge zone.

Another method for assessing the power distribution was proposed by B.M. Strunsky [21], based on replacing the high primary voltage of the furnace transformer with a reduced voltage (220–560 V). As a result, due to the drastic decrease of the voltage on the electrodes (down to 2–3 V), arc burning ceases, allowing, without changing the electrode position, the measurement of the small charge conductivity currents and subsequent calculation of the power and resistance values for the individual zones.

The value of such studies lies in the indisputable evidence of the existence of charge conductivity currents and the ability to estimate the share of charge power in the total phase power. However, probing methods are extremely labor-intensive and require complex experimental equipment, and the methods involving electrode lifting and primary voltage reduction significantly impact the main characteristics and the course of the process. Therefore, these methods cannot be fully applied for real-time monitoring of the energy parameters of the furnace workspace zones.

In this context, direct measurement methods of electrical parameters are of great practical interest. The essence of most of these methods lies in complementing the system of equations describing the electrical regime of the process with the characteristic features of any element of the substitution scheme. In particular, the arc discharge, which has pronounced nonlinear electrical properties, is used.

An example is the method proposed by N.A. Markov [22], based on the following principle: depending on the change in the charge resistance, the neutral point shift occurs - the voltage between the artificial neutral of the furnace transformer’s low side and the bath neutral. It is known [22] that in the presence of a nonlinear element in the circuit, under a symmetrical supply voltage system and symmetrical loading, this voltage results from the third and higher odd harmonics of the phase voltages of the furnace.

Based on the calculated dependencies of U00 on the charge current at different values of charge and melt resistance, the values of rch and rm are determined. The main disadvantage of this method is that it applies only under conditions of complete symmetry of the electrical regime, which is practically unattainable in industrial furnaces.

Another method based on the determination of the third harmonic in the "electrode-bottom" voltage signal was proposed by S.A. Morgulev [23]. Neglecting the charge conductivity currents and assuming a rectangular shape for the arc voltage, the arc voltage drop is calculated as three times the third harmonic voltage. However, many researchers have both theoretically and experimentally shown that charge conductivity currents do exist, and in slagless processes, they can be three or more times higher than the currents flowing through the "arc-melt" circuit. Thus, this method is not suitable for the calculation and monitoring of energy distribution among individual furnace zones.

V.M. Frigin [24] proposed a method to determine the charge and arc currents in electric arc reduction furnaces operating under slagless technologies. A sinusoidal voltage Us from an external source is applied counter to the furnace voltage


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(presumably the phase voltage drop). Given that the shunted arc burns intermittently, and by adjusting the amplitude and phase of the external signal, a differential signal Up is obtained on the oscilloscope screen.

The tuning criterion for this signal is the appearance of straight-line sections corresponding to arc current pauses on the time axis of the oscillogram. Correctly assuming that without arc current, the entire current flows through the charge, and accepting that the charge current is proportional to the furnace voltage, it follows that by measuring Up and Us and knowing the effective furnace current, one can determine the arc current and then calculate the charge current according to Kirchhoff’s first law.

A variation of the method involves determining the total charge resistance Zch based on the tangent of the slope of the dynamic CVC built on the oscilloscope screen, accounting for scaling coefficients. The main advantage of this method compared to the previously discussed ones is that it allows real-time monitoring and tracking of changes in current distribution and power among the "charge", "arc," and "melt" zones, as well as the charge resistance value, without the use of complex equipment and without interfering with the technological process.

As a result of the review of power distribution assessment methods across furnace bath zones, various data obtained by different researchers are summarized. However, data on energy distribution in slag processes are almost absent, and for slagless processes, the results vary significantly.

For example, B.M. Strunsky, using the method of replacing the high voltage with a reduced voltage when studying the modes of a carbide furnace, obtained the following power distribution across zones: 27–30% in the charge, 40–50% in the arcs, and 32% in the melt. Applying the same method for studying the power distribution in a furnace smelting 75% ferrosilicon, Weinstein and Yermolovich found: 56–64% in the charge, 29–32% in the arcs, and 7–8% in the melt.

According to V.M. Frigin, in most cases, the share of arc power in the total phase power is 18–23%, although in some cases it may reach 50–60%.

Achieving high techno-economic indicators in ferroalloy technologies critically depends on rational and efficient process control. However, the differing inertia of processes in the furnace bath necessitates the separation of subsystem controls for individual technological modes within the general control system.

The tasks of process control are closely linked to the tasks of optimizing the energy and technological parameters. Two optimization paths can be distinguished, differing in their goals:

Selecting rational geometrical and electrical parameters (bath diameter, electrode diameter and spacing, total transformer capacity, and secondary voltage) when designing new furnaces or reconstructing existing ones.

Optimizing the parameters of individual technological modes.

The first path was proposed by A.S. Mikulinsky [25] and is based on the theory of similarity. A working furnace with lower capacity but optimal techno-economic performance among similar ones is chosen as a model. Based on the condition of ensuring a given electrical energy distribution under optimal electrode immersion, a similarity criterion for the electric field was derived using Ohm’s law in differential form.

I.T. Zherdev shared similar views, although he noted that the relative geometric parameters depend on the furnace power. In practice, it has been shown that similarity constants are not universal and require adjustment when calculating parameters for furnaces producing different alloys.

V.A. Ershov and V.L. Rozenberg determined that this dependence is statistical, and the similarity parameter (p) can vary between 0.25 and 0.33, with the coefficient C depending on the conditions of the chemical processes: reagent activity, product composition, average temperature, and granularity of the charge. Thus, as the authors note, the concept of a “reference furnace” loses its meaning.

The second approach in solving optimization tasks is associated with determining the optimal parameters of separate technological modes that affect each other, and identifying the nature of their interdependence. Measurements of parameters are based on the method of comprehensive furnace research.

In the monograph [26], V.I. Zhuchkov and V.L. Rozenberg highlighted the main tasks solved by this method:

- Identifying limiting structural elements in terms of reliability;
- Determining optimal operating modes to achieve maximum productivity;


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- Obtaining initial data for automated process control;
- Defining technical requirements for the type and quality of charge materials;
- Obtaining data for the design of new, modern, and more powerful aggregates.

However, a significant disadvantage of this method is that its application involves the use of special equipment (probes, a large number of measuring devices) and the high labor intensity of experiments, which excludes its use for real-time monitoring of the process state.

Clearly, solving optimization, control, and monitoring tasks must be increasingly oriented toward the development and application of indirect methods for process state evaluation [27–29].

Long-observed trends, such as the decrease in charge material quality (ores and reducing agents) and the sharp reduction in bath active resistance due to increased furnace unit power, have determined the main optimization directions, including:

- Replacing part of the expensive carbon reducer with a cheaper one;
- Selecting the optimal chemical and granulometric composition of the carbonaceous part of the charge to ensure maximum bath resistance;
- Determining the optimal electrode immersion depth and movement patterns during smelting cycles;
- Studying the influence of the carbon excess coefficient in the charge on process indicators;
- Selecting optimal electrical mode parameters.

## Conclusions

The effective control and optimization of the techno-economic performance of ferroalloy smelting processes in electric arc furnaces are impossible without the application of modern automated monitoring and production control systems. Despite the significant advancements in computing technologies that began in the early 1990s, the current level of automation in ferroalloy production remains insufficiently developed. Most furnaces are still equipped only with automatic regulators for electrode movement, and only in isolated cases have systems been introduced for managing charge weighing and dosing regimes, typically designed by in-house specialists.

The creation of multi-level automated control systems for ferroalloy smelting technologies therefore remains a highly relevant and urgent task. Transitioning from traditional "input-output" control models to more advanced "input-state-output" models is essential to significantly improve process efficiency. Such a transition would allow real-time monitoring and comprehensive analysis of the state of the furnace workspace, enabling operators to make timely and more accurate corrective actions.

The studies presented emphasize that achieving high techno-economic performance requires a deeper understanding of the complex and interconnected physico-chemical, thermal, and electrical processes occurring within the furnace bath. Special attention must be given to the optimization of energy distribution among the furnace zones (charge, arc, melt), as the efficiency of these processes has a direct impact on energy consumption, material yield, and product quality.

The implementation of indirect methods for evaluating the state of the furnace, based on the analysis of electrical parameters without interfering with the technological process, represents a promising direction for enhancing control quality. Furthermore, research demonstrates that developing mathematical models of furnace behavior, identifying optimal technological parameters, and formalizing control procedures can significantly reduce the dispersion of process fluctuations, minimize material and energy losses, and improve the stability of furnace operations.

Future development efforts must focus on:

- Increasing the depth and accuracy of real-time process diagnostics;
- Creating adaptive and predictive control systems based on data-driven modeling;
- Integrating intelligent decision support systems to assist operators;
- Expanding the scope of automated monitoring to include not only electrical, but also chemical and thermal parameters.


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The solutions outlined in this work create a foundation for the future transition to smart ferroalloy production technologies that meet modern requirements for energy efficiency, environmental safety, and high product quality.

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# ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ПРОЦЕСУ ВИПЛАВКИ ФЕРОСПЛАВІВ В ЕЛЕКТРОДУГОВИХ ПЕЧАХ ШЛЯХОМ ВДОСКОНАЛЕННЯ КОНТРОЛЮ ТА КЕРУВАННЯ ТЕХНОЛОГІЧНИМИ РЕЖИМАМИ

**Анотація.** *У статті розглянуто проблеми підвищення ефективності виплавки феросплавів в електродугових печах шляхом удосконалення контролю та управління технологічними режимами. Світові тенденції, що спостерігаються останніми роками, такі як збільшення виробництва високоякісних легованих сталей та напівпровідникової продукції, визначили стрімке зростання попиту на*


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*феросплави та кристалічний кремній. У зв'язку з цим особливої актуальності набувають питання інтенсифікації технологічних процесів та оптимізації енергетичних витрат у феросплавних електропечах.*

*Процес виплавки феросплавів базується на карботермічному способі відновлення металів із їх оксидів, що протікає при високих температурах із поглинанням значної кількості тепла. Попри те, що механізм та кінетика основних відновлювальних реакцій добре вивчені, у промислових умовах техніко-економічні показники процесу істотно поступаються лабораторним. Ступінь вилучення цільових елементів знижується до 75–80%, а витрата електроенергії перевищує теоретично необхідну у 1,5–2 рази.*

*Традиційні підходи до вдосконалення процесу виплавки феросплавів шляхом покращення конструкції печей і підбору фізико-хімічних властивостей шихтових матеріалів вичерпали свій потенціал. В умовах постійного зростання цін на енергоресурси та погіршення якості сировини нагальною проблемою стає впровадження принципово нових підходів до керування технологічним процесом, орієнтованих на детальний контроль та аналіз поточного стану печі.*

*Автори обґрунтовують необхідність переходу від системи керування за принципом «вхід-вихід» до більш прогресивного принципу «вхід-стан-вихід», що дозволяє в режимі реального часу аналізувати параметри робочого простору печі та оперативно впливати на хід технологічного процесу. Зокрема, значна увага приділяється розвитку методів аналізу електричних, теплових та фізико-хімічних характеристик активної зони печі, що визначають хід основних процесів перетворення шихти.*

*У роботі розглянуто конструктивні особливості електродугових печей, описано будову робочого простору для різних типів процесів - безшлакових та шлакових. Показано, що форма розподілу енергії між зонами шихти, дуги та розплаву має суттєвий вплив на техніко-економічні показники виробництва. Вивчено особливості горіння дуги, процеси теплообміну та іонізації в газових порожнинах печей.*

*Стаття висвітлює основні методи дослідження процесів у печах: зондування, аналіз осцилограм струму та напруги, визначення опорів шихти та розплаву, а також новітні методи оцінки розподілу потужності по зонах печі на основі вимірювань електричних параметрів. Особливої уваги надано проблематиці*

*підвищення точності оцінки параметрів енергетичних процесів без втручання в технологічний процес.*

*Автори обґрунтовують важливість оптимізації режимів електропостачання та конструктивних параметрів печей для забезпечення стабільності роботи ванни, зниження дисперсії коливань та мінімізації втрат. Наведено методи вибору оптимальних параметрів занурення електродів, управління шихтовими режимами, підбору шихтових матеріалів із урахуванням їх електрофізичних властивостей.*

*Стаття робить вагомий внесок у створення наукової основи для підвищення ефективності виплавки феросплавів, що має особливе значення в умовах сучасної енергетичної кризи та зростання вимог до якості продукції металургійної промисловості.*

**Ключові слова:** *виплавка феросплавів; електродугова піч; карботермічне відновлення; автоматизоване керування; техніко-економічні показники; розподіл енергії; дуговий розряд; оптимізація процесу; шихтові матеріали; енергетичні витрати; контроль стану печі.*

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