RESEARCH OF THE OPERATION MODES OF SELF-BAKING ELECTRODES OF HIGH-POWER ELECTRIC ORE-SMELTING FURNACES AT PJSC "NIKOPOL FERROALLOY PLANT"

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ABSTRACT

The regularities of the temperature distribution and the location of the type of aggregate zones of self-baking electrodes in high-power furnaces have been identified. Optimal operation modes during furnaces shut downs are identified and implemented at PJSC "NFP"; this provides a uniform ratio of cooling rates for the center of the electrode and its surface reducing the number of the breaks, which improves furnace performance and reduces the cost of electricity and charge materials. A mathematical model has been created for calculating thermal fields of round and flat self-baking electrodes applied to different types, designs and capacities of furnaces and also types of melted alloys was developed. Investigations of microstructure as well as physical and mechanical properties of the flat sheet metal samples heated to 1300°C in oxidizing and low-oxidizing gaseous media in the contact with the electrode paste were carried out. The electrode shell building technology have been studied, conditions and features for joint weld formation have been considered using different grades of steel, types of joint weld and welding process, the method of semi-automatic welding of self-backing electrodes shells hasbeen studied and implemented at PJSC "NFP" by solid and flux cored wire in carbon gas medium.

1. INTRODUCTION

Creating the optimal operating conditions for continuous self-baking electrodes of iron-smelting electric furnaces with complex and diverse physical and chemical processes occurring during the firing of electrode gives rise to the urgent need to study the thermal and technical characteristics of the electrode formation. Therefore, the information about temperature distribution along the height and cross-section of the electrode as well as the position of particular areas of the aggregate state of electrode paste becomes important, so as to allow the development of specific suggestions to eliminate breaks of electrodes on coked and uncoked parts [1].

2. EXPERIMENT

For investigation of the temperature fields of self-baking electrodes of electric ore-smelting furnaces one of the most reliable though labour-consuming method of anadromous thermocouples was used [1]. Chromel-Aluminium thermocouples isolated from the external environment by alundum strips were placed in a tube pre-installed in the electrode with a diameter of 1 inch following the schematic shown in Figure 1. The working end of the thermocouple was protected by a corundum cap 60 mm long. This was necessary to prevent it from carburization in the high-temperature zone. The load was attached to the corundum cap with nichrome wire. As the electrode was being built-up the sections of the pipes with a high equal to that of the shell were connected via joints. Welded pipes connections were not used because they made it difficult to move the thermocouple wire (Figure 1).

The coordinates of the points at which the temperature was measured were determined by the formula: $X = (H + h + l) - (A + L)$, where H - the distance from the bottom edge of the thrust ring to the upper edge of the contact cheeks; h - height of the contact cheeks; l - distance from the top edge of the shell to the bottom edge of the housing of the thrust ring; L - length of the tube; A - distance from the top of the pipe to the upper edge of the shell. Thermal emf was measured by recording electronic potentiometer KSP-06 with chart strip velocity of 60 mm/h. Temperature measurement was carried out by moving the thermoprobe along the electrode height and by holding it at each measurement point till the equilibrium was established, but not less than 10 minutes. The reference point was the lower edge of the contact cheeks. Studies of temperature zones were carried out at discrete change of power in the range of 50-55 MW and the current equal to an average of 90 - 100 kA. Measurements of thermal fields were carried out after the furnace operation at a given electric mode for at least 1 day.

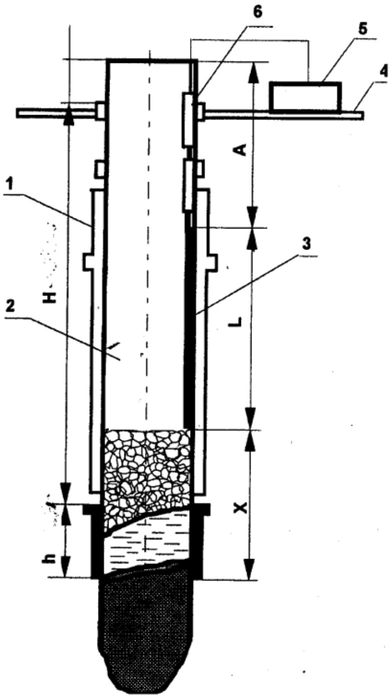

Fig. 1. Schematic of thermocouples arrangement in the study of temperature fields of the electrodes 1 - supporting cylinder; 2 - electrode; 3 - a pipe with thermocouple; 4- electrode area; 5 - potentiometer; 6 - protective angles.

3. RESULTS

The results of studies of the electrode thermal field of RPZ-63 at Nikopol Ferroalloy Plant duringsilico-manganese smelting (a) and ferromanganese (b) operating at a power of 52-55 MW and 95-100 kA electrode current are shown in Fig. 2.

a

air

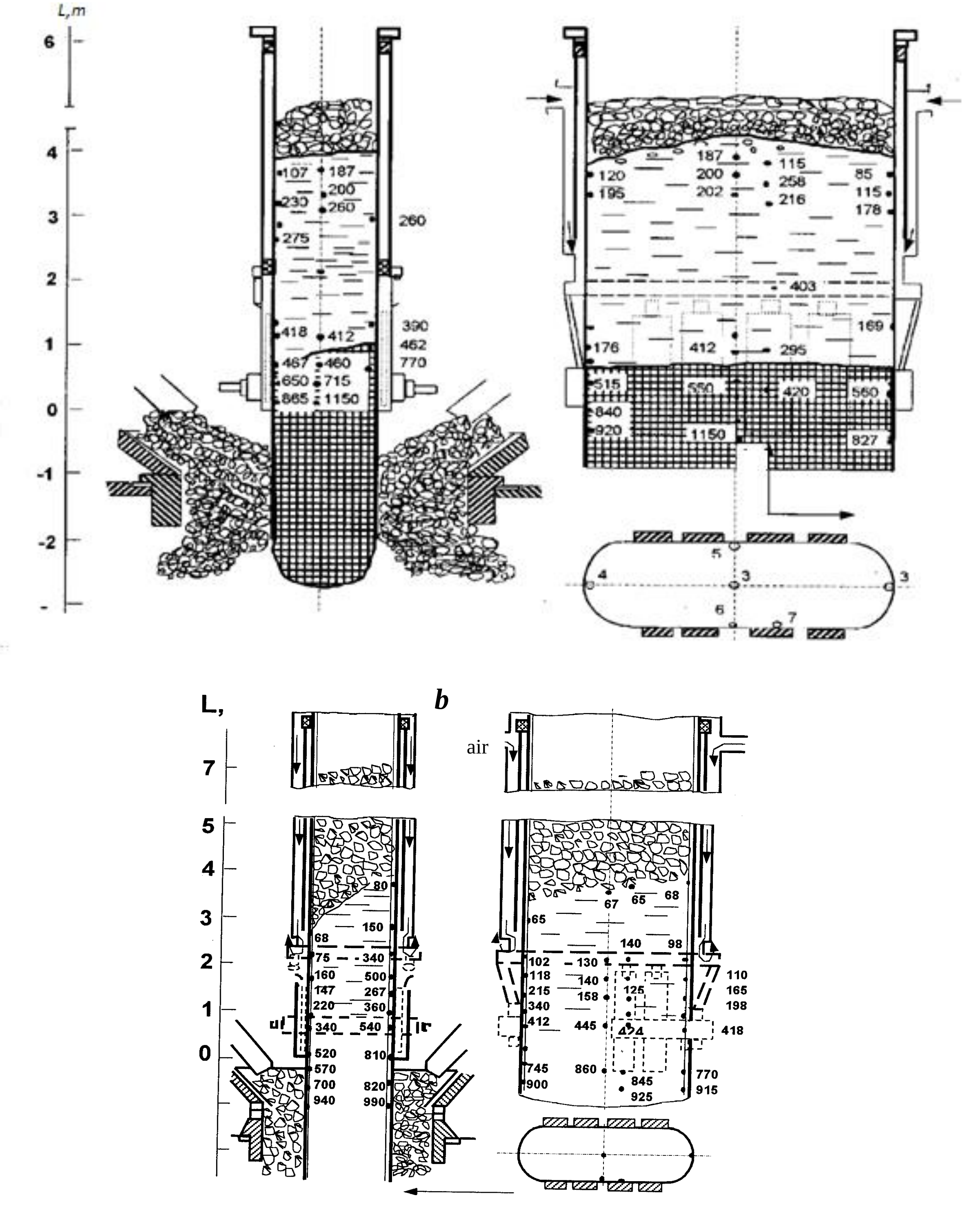

Fig. 2. Temperature field of the electrode ofRPZ-63 furnace when: (a) silico-manganese smelting, (b) ferro-manganese smelting.

Comparative analysis of the distribution of temperature zones and forms of isothermal surfaces in the electrode of the RPZ-63 furnace whilst smelting ferromanganese made with similar data for rectangular silico-manganese furnaces RPZ-63 (Fig. 2) shows that the main regularities of temperature field distribution in rectangular self-baking electrodes of RPZ-63 furnaces are retained irrespective of the melted alloy type, smelting method and furnace capacity. The shape of the isothermal surfaces bounding the melting and electrode paste coking zones are both convex and concave. The surface curvature in the longitudinal direction (along the major axis) is slightly larger than in the transverse dimension. Convex nature of the isothermal surface of the upper coking zone obtained during the study of the electrodes of ferromanganese furnaces shows that the proportion of 'Joule' heat during coking of the electrode paste is slightly lower than the heat coming out of the furnace bath. This is due to comparatively small size of the rectangular electrodes along the minor axis.

The isothermal surface of the lower part of a coking zone (isotherm 600^0C) is slightly convex. Furthermore, the temperature of the central part of the electrode below the coking zone increases at a greater rate than at the periphery. It seems likely that in the coked carbon block of the electrode the cooling effect of continuously uploaded charge as well as the heat supplied through the electrode from the furnace bath greatly affects temperature distribution. The temperature of the peripheral layers of the electrode is under significant impact of the conditions of contacting and cooling of the contact cheeks. Near the upper edge of the cheeks temperature difference between the center and the surface of the electrode may reach 1000°C or more. In this case the heat is likely to abstract through the shell [2].

One of the most important features of the temperature zones distribution is pronounced slope of isotherms at the beginning of electrode paste coking, whereby the side of the electrode facing the homonymous phase is hotter which is also typical for silico-manganese rectangular furnaces. In some cases, the temperature difference reaches 200-250^0C or more, which is extremely undesirable since it contributes to the development of desintegration (sedimentation) of the electrode paste components, and as a result, leads to deterioration of the operational stability of the working electrode edge. It seems necessary to introduce minor changes in the blasting systems design to obtain the opportunity to more intensively blow 'hot' side of the electrode that will allow reducing or eliminating the asymmetry of the electrode thermal field.

The most important indication of the reliability of the self-baking electrode area is the level of zone where coking begins (isotherms of 400-600^0C). The studies carried out suggest that in RPZ-63 furnaces during carbon ferromanganese smelting at a power of 52-55 MW the coking zone is at 350-450 mm above the lower edge of the contact cheeks, in some cases - lower. Such a position of the coking zone can be considered optimal in practice though with increasing power of the furnace it may be necessary to develop activities that heighten the level of coking zone.

4. DISCUSSION

Electric furnaces by Tanabe-kakoki (Japan) with an installed capacity of the transformer at of 81 MVA and three self-baking electrodes with a diameter of 2000 mm installed in the Nikopol Ferroalloy Plant constantly require the solving of issues of furnace equipment reliability, in particular, with the self-baking electrodes. Installed power of the furnace transformer RKG-75 is 81 MVA, while actual operating power is 45 MW, design capacity of 90 thousand tons per year.

The hydraulic hoisting mechanism for movement of the electrode is equipped with two cylinders, however, the electrode goes down under its own weight. To prevent lateral displacement of the electrode guide rollers are mounted. Operating pressure in the cylinder is 140 kg/cm2. The mechanism of the electrode bypass is a hydraulically driven system with two friction steel straps. The upper friction strap is supported with 4 hydrocylinders. The electrode clamping with friction straps is made by cylinders with a force of 50 tons. Operating pressure in the cylinder is 112 kg/cm^2 and stripping of 15 mm. Frictional straps fastening tape rate is 1000 mm/min.

The bypassing control can be manual and automatic, the single bypass value is 10 mm. RKG-75 furnace design also features an electrode clamping device which is a cone clamping system. Both the outer side of the contact cheek of the electrode and a ring surrounding the contact cheeks are conical. When the conical ring is moved up or down through hydromotor the contact cheeks are fastened or loosen relative to the electrode (Figure 3.). Contact cheeks clamping is always consisting of : hydromotor, reducer, cylindrical spur wheel, drive shaft, sprocket, lantern gear, sprocket, lifting and descending shaft of the cone ring, cone ring, contact cheeks (Fig. 3.) of the electrode [3].

The results of the studies to determine the temperature fields of the electrodes show that when the furnace operates at the power of 42-45 MW, operating current of 145-150 kA and an average consumption of electrode 550 mm/day, the coking isotherm was concave and was located at the level of +550 and +200 mm of the hot and cold side, respectively. The height of the column of molten mass ($100\div350^0$C) reaches 1.5-2.0 m and softening point isotherm ($70\div100^0$C) is at 1.3÷2.3 m above the bottom edge of the contact cheeks. Contact cheeks have a very significant cooling impact on the electrode. Due to this fact, below the coking zone, the temperature drop in the areas that are in contact cheeks and between them reaches 100-120^0C (Fig. 4). The temperature of underroof in the electrode area reaches 1000-1100^0C.

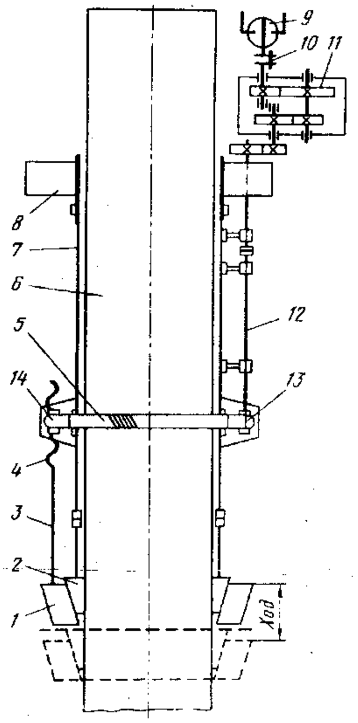

Fig. 3. Schematic of clamping contact device operation

1 - cone ring; 2 - contact cheeks; 3 - lifting and descending shaft; 4 - screw; 5 - gear wheel; 6 - electrode; 7 - supporting cylinder; 8 - supporting cylinder ring; 9 - hydromotor; 10 - coupling; 11 - reducer; 12 - drive shaft; 13; 14 - sprockets

The relatively low position of the coking area requires strict compliance with the electrodes bypass modes (100-200 mm three times a day) and, accordingly, with the blasting modes at different times of the year, providing high-quality shell weld joints and uniform uploading of the electrode paste. High reliability of operation of the furnace RKG-75 electrodes is achieved by using sheet steel housing 4 mm thick. To heighten the coking zone, , it was recommended to develop and introduce higher quality thermal conductive electrode paste containing silicon carbide [3].

Over the recent years, the practice of operation of electric ore-smelting furnaces has shown that often limitations of the companies energy use force them to reduce and sometimes even shut down electrometallurgical units for certain periods of time. This has a negative impact on the operational stability of self-baking electrodes, as about 80% of their breaks occurs after the "hot" and "cold" downtime and thermal stresses occurring in the body of the electrode during prolonged shutdown. During the shutdown of the furnace the cooling rate of the outer electrode surface reaches 160-180^{0}C per hour, which is 8-10 times greater than the permissible cooling rate in the manufacture of molded carbon and graphite electrodes that results in much larger temperature gradient over the cross section than that which existed in the operating electrode. When the resulting thermal stresses exceed the limit of the mechanical strength of the electrode material, the crack is formed in the surface layer.

When the furnace is connected to the current load the thermal expansion coefficient increases dramatically and the gap between the cracks also increases. In the areas where the cracks develop there is additional electrical resistance where significant amount of heat is generated. The temperature at the contact point increases. Intensive oxidation of the carbon components which come up onto the surface of partition occurs. When the current load after the furnace shutdown increases, the electrodes usually break, the period for the furnace to reach its full capacity is delayed, and performance decreases [1, 2].

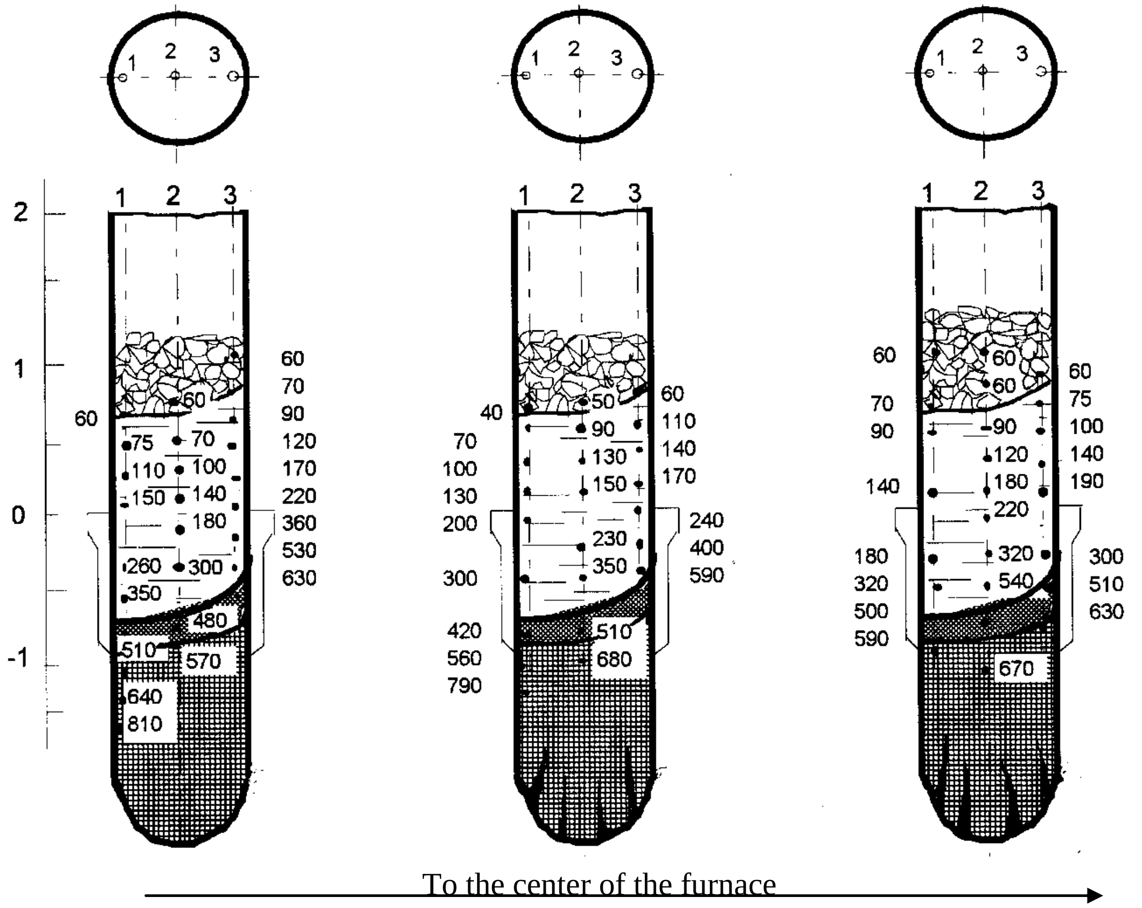

Fig 4. Temperature fields of the electrodes of three-electrode electric furnace RKG-75 for ferroalloys smelting

A practice of slow gaining of power after a long furnace downtime has been applied in order to prevent sudden thermal shock. In our opinion, this method has no significant effect on the durability of the electrode. When the furnace is turned on after a downtime, the electric current passing through the surface layers of the electrode heats them and thereby eliminates occurring thermal stresses. However, if the cracks were formed in the electrode during downtime, slow heating only postpones the electrode break but does not prevent it.

At PJSC “NFP” and PJSC “ZFP” the investigations have been carried out and the temperature difference between the center and the surface of the electrode during the furnace shut-down and subsequent power gain have been determined. Temperature gradient at the unregulated furnace shut-down mode reaches 400-500^{0}C (Fig. 6)

In order to prevent breaks associated with shut-downs and prolonged downtime, a method for the preparation of electrodes for the furnace shut-down has been developed and implemented, which is based on the principle of a smooth cooling of the electrode surface by reducing the current load. During the period of 2-3 days before shutting down the furnace the electrodes are shortened by 400-500 mm by reducing or stopping the bypass; during 6-8 hours before the shutdown load current is gradually reduced to 20-30% of the nominal value bypassing the electrodes and shutting down the furnace.

This mode enabled cooling of the center and on the surface of the electrode by 200-300^{0}C at the same rate, and to move the area mostly prone to cracking towards the furnace roof, that is to reduce the rate of further cooling. Ultimately, the maximum temperature difference did not exceed 200^{0}C and this significantly increased electrode durability. After the introduction of the developed mode in 16 electric furnaces (78 electrodes) the number of breaks decreased by 47.7%, thereby increasing performance and reducing energy consumption (Fig. 5).

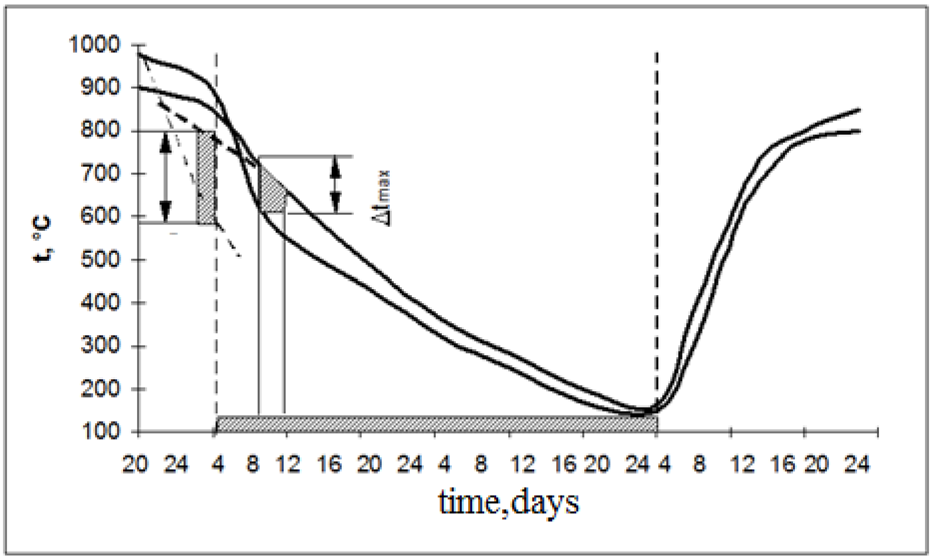

Fig. 5. Temperature change in the self-baking electrode of RPZ-63 furnace after its shutting-down

The need for a PC simulation of electric and thermal fields of self-baking electrodes of ore-smelting electric furnaces arises both at the design stage and when developing and optimizing techniques in the process of operation. To this effect, algorithms and software package have been developed that allow the simulation of the thermal fields of the electrodes of ferroalloy furnaces. The software is written in the algorithmic language Turbo Pascal and C ++ and does not require any special system-dependent tools throughout its operation [4-8].

Construction of a mathematical model was preceded by systematically considering the influence of the main technological, electrical and design parameters. The model is based on the equation of heat distribution in the electrode accounting for the influence of various factors. Models are compared with their numerical and analytical analogues which check the the accuracy, the analytical and computational simplicity of numerical solutions, and the processability of information transfer between the internal nodes of the grid area and the limit where single value conditions are set. For the construction of adequate and efficient algorithms for solving a system of differential equations in partial derivatives describing thermal fields of the electrode finite-difference methods and the method of splitting the spatial variables of Peaceman-Rechford were used, allowing us to reduce the algorithm to the scalar marching and thus to build an efficient scheme in terms of the number of arithmetic operations.

While constructing the model the equations and boundary conditions were used that adequately describe the real processes occurring in each temperature zone of the electrode. the equation was used for areas of solid paste heat conduction, and the Navier-Stokes equations applied for viscous non-compressible fluid was used for “liquid zone”. A set of basic problems arising in the analysis of temperature fields of the electrodes of iron-smelting furnaces allows for consolidation of equations, the single-valuedness conditions and their recording in a standardized form:

$$\frac{\partial Y}{\partial \tau} = A(Y)\nabla^2 Y + B(Y)\frac{\partial Y}{\partial y} + C(Y)\frac{\partial Y}{\partial x} + D(Y)\frac{\partial Y}{\partial z} + W, where \quad Y = \begin{Bmatrix} T_k \\ \varphi_k \end{Bmatrix}, \quad k = 1,2,3,\ldots$$

The vectors of the desired function of temperatures ordered by the k zones of the electrode; A(Y), B(Y), C(Y), D(Y) are known functions describing physical and mechanical, thermal and physical as well as electrical properties of the electrode paste; W - vectors of sources characterizing heat transfer from the furnace, specific heat of the electrode paste coking, :Joule heat” of the electric current, heat of flue gases, heat transfer to the environment and the charge with the cooling water for heating and melting of the paste, etc. Initial and boundary conditions are applied to the dynamics of the process.

In the analysis of the various methods for solving the set the method of splitting by spatial variables was preferred, which allowed building a compact system of algorithms to implement solutions to this class of problems, and supplementing a set in case of an increase in the number of factors influencing the temperature field.

The program is based on the idea of structured programming with step-by-step refinement of tasks and the development of the structural models. The individual parts of the program are presented in the form of functions-operators, localized in one place in the program, which is convenient when you make changes to the program.

The programming means allows entering of the initial data required for calculation, analysis and processing of the results, as well as presenting them in the form of tables and figures. The developed set of programs of the automated system of thermal analysis can be used to detect and predict the conditions of rational conditions of the electrodes formation.

To identify the processes occurring in the electrodes, a method based on the principles of the solution of inverse heat transfer problems is suggested, in case if on the basis of some information about temperature or electric fields, known from the experiment, it is necessary to determine any causal characteristics. The most characteristic inverse heat transfer problems are classified with respect to the operation of self-baking electrodes. The models, algorithms and software for solving boundary inverse heat conduction problems have been developed for the identification of heat transfer processes in a self-baking electrode. The algorithm has an incremental regularization; it received certification based on analytical solutions of the theory of heat conduction, and is simply generalized to the solution of other classes of inverse problems and can be recommended for the practice of processing and interpretation of thermal measurements data in relation to the identification of the processes of heat transfer in self-baking electrodes of ore-smelting furnaces.

Results of the research into microstructure as well as physical and mechanical properties of sheet (2-4 mm) metal used for manufacturing of shells of the continuous self-baking electrodes heated up to 1300^0C in a low-oxidizing and oxidizing media in contact with the electrode paste have been investigated. The samples cut from the electrode shell of the ore-smelting furnaces at their shut-down were also investigated. With increasing temperature, the mass loss of sheet metal in an oxidizing medium increases and at 1000^0C the samples were almost completely oxidized. Strength and plastic characteristics also decreased in this case. Metal heated in a low-oxidizing medium oxidizes slightly with the increase of temperature up to 1200°C [9].

In the absence of contact with the electrode paste at $800\text{-}900^0$C an increase in the metal grain and partial decarbonization is observed. The samples heated in an environment of electrode paste underwent significant carburization. At 1250^0C the metal structure corresponds to perlite. In the electrode shell metal of the furnace RPZ-63 sampled near the lower edge of the contact cheeks, there is a substantial grain growth. In the area 0.5 m below the cheeks the metal is strongly carbonized. The initial ferritic structure is transformed into ferrite-perlite one which is accompanied by an increase in the σ gap to 540-584 MPa. * The values of σ decreased to 3.2-5.2%.

Type of weld	Steel grade	Sheetthickness mm.	σ,kg·s/mm^2 at temperatures, ^{0}C		
			20	300	600
Control, withoutt weld joint	SCS	4.5	46.7	43.6	10.28
	SCS	3.9	42.6	39.8	8.84
	SCS	3.0	38.3	35.1	7.96
Overlapped	SCS	3.9	41.3*	29.2*	5.48*
in a butt joint without a gap	SCS	3.9	39.2*	31.5*	5.5*
	SCS	3.0	37.5*	29.0*	7.5*
in a butt joint with a gap of 3 mm	SCS	4.5	40.7*	33.5*	6.8*
in a butt joint with a gap of 10mm, triple joint	SCS	4.5	48.7	39.0	8.4

*Break along the weld joint

Table 1: The mechanical characteristics of welded and solid samples at different temperatures (heating by electric current)

In the course of the research on a unit specially created for mechanical testing of samples under current load, the temperature dependence of mechanical properties of solid and welded samples of the type of low-carbon steels on the type of welds was defined. It has been established (Table. 1) that the metal welded in a butt joint has ultimate tensile strength by 10-30% lower than that of the whole sample. It has been determined that the samples of the shell made of structural carbon steel of ordinary quality (SCS) welded by ANO-4 electrodes in a triple butt joint according to all the technological requirements, have mechanical tensile strength greater than that of whole sample.

The obtained results show that the technique of growing the shell sections (total height of the shell is 15-20 mm) is of great value especially for the furnaces RKG-75 where the only permissible type of weld joint is a triple one.

The research results allowed to develop and implement at PJSC "NFP" the method of semi-automatic welding of steel shells of self-baking electrodes with solid and cored wire SV-08.G2S in CO_2 medium, ensuring high stability of the welding process, improving the quality of welded joints, increasing durability of the electrodes and significantly reducing the labor input of the operation of shell growing.

CONCLUSIONS

The regularities of the temperature distribution and the nature of the location of aggregate zones of self-baking electrodes of the electric furnaces RKZ, RPZ and RKG are identified. Optimum operation modes during shutting-down of furnaces have been determined and implemented at PJSC "NFP" to provide a uniform ratio of cooling rates for the center and the surface of the electrode allowing for reduction of the number of their breaks, increasing performance of furnaces, reducing the cost of electricity and charge materials.

Algorithms and programs set for PC calculation of the thermal fields of self-baking electrodes have been developed in non-stationary formulation based on two and three spatial dimensions. This mathematical model allows the calculation of thermal fields of round and flat electrodes both at the furnaces design stage and during the optimization of techniques in the process of operation. A program written in an algorithmic language Turbo Pascal and C++ is developed in the form of an automated system of thermal analysis for PC.

Some research has been carried out on steel used in manufacturing of electrodes shells at heating in an oxidizing and low-oxidizing gas media in contact with the electrode paste at temperatures up to 1300°C, and on samples cut from the electrode shell of the operating furnaces during their shutdown. It has been determined that the microstructure and properties of steel shells of the electrodes during their formation undergo significant changes and reflect complex physical and chemical processes and temperature conditions of interaction with the electrode paste and the environment.

The analysis of the conditions and characteristics of the electrodes shell growing technique when using different types of welding was carried out; the semi-automatic method of self-baking electrodes shells by solid and cored wire in carbon dioxide medium has been studied and implemented at PJSC “NFP” that ensured high stability of the welding process, improving the quality of weld joints, increasing durability of electrodes and reducing the complexity of growing operations.

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