The article analyzes the Mathematical Model of The Self-Baking Electrode which is defined as basic. Its advantages and disadvantages are determined. Criteria for creating more advanced mathematical model for equalizing the thermal field of the Electrode are proposed.

The problem of calculating the thermal field is solved by the method of elementary heat balances of electrode. For this goal the simulated area is divided into annular (cylindrical) elements along the radius and height of the electrode. The calculation of the temperature field of the electrode is carried out in two stages: I – with boundary conditions and currents for the parts of the electrode facing to the center of the smelting furnace; II – with boundary conditions and currents for the parts of the electrode facing to the lining.

The mathematical model takes into account an effect of the ribs and the hood on the distribution of electric current and Joule’s Heat over the cross section of the Electrode. In case heating ferromagnetic materials under impact of an electromagnetic field, the magnetic permeability at first decreases relatively slowly, and then dropping down sharply as a certain temperature (Curie Point) is reached. The material loses its magnetic properties completely and goes into into a paramagnetic state.

The value of the electrode current changes according to the graph from the starting value to the working value and then remains constant. The current density along the radius is unequal due to the action of the surface effect, as well as due to existence of a metal hood and ribs, the electrical conductivity of which is higher than conductivity of special carbon paste.

The goal of the work is to create modern mathematical model of the secondary current network of electric smelting furnace which could improve baking conditions of the Electrode and to reach the state of its temperature field to equable. This would create a stable mode of operation of the furnace. The paper analyzes the main features of the mathematical model of the secondary network of the smelting furnace, identifies the stages of development and formulates the main assumptions simplifications that could be accepted while creating this model.

Keywords: Mathematical Model, Self-Baking Electrode, Electrode’s Electric Current, Thermal Field.

Introduction. The article analyzes The mathematical model of the self-baking electrode which is defined as basic. Its advantages and disadvantages are determined. Criteria for creating more advanced mathematical model for equalizing the thermal field of the Electrode are proposed.

Problem statement. The problem of calculating the thermal field is solved by the method of elementary heat balances of electrode. For this goal the simulated area is divided into annular (cylindrical) elements along the radius and height of the electrode.

Analysis of recent years research and publications. There are well known mathematical models of a self-baking electrodes [1, 2, 3, 4, 5]. The most successful is the mathematical model [2] which is accepted as the basic for research.

The self-baking electrode is made of metal (steel) hood and filled by a special mass so called unbaked carbon paste. The hood with internal ribs serves as a forming shell for the electrode mass and provides an alternating electric current flow to its lateral surface by special contact’s cheeks.

The contact of electrode-contact’s cheek is not ideal. the contact pressure is considered to be known and for all cheeks are the same.

The value of the electrode current changes according to the graph from the starting value to the working value and then remains constant. The current density along the radius is unequal due to the action of the surface effect, as well as due to existence of a metal hood and ribs, the electrical conductivity of which is higher than conductivity of special carbon paste.

The electrode baking takes place due to Joule’s Heat and heat from the smelting bath. The electrode carbon paste goes through all stages of phase transformations gradually [7].
The purpose of the article. The goal of the work is to create modern mathematical model of the secondary current network of electric smelting furnace which could improve baking conditions of the Electrode and to reach the state of its temperature field to equable. This would create a stable mode of operation of the furnace.

Results of the research. The operating conditions of the electrode allow to distinguish four characteristic zones according to its height, so electrode column is divided into parts Fig.: the zone of the charge (bottom end of the electrode); free zone from the level of the charge to the lower edge of the contact cheeks; cheek area; the mantel zone is above the upper level of the contact’s cheeks.

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The temperature of the吹入 air is specified in a space of the mantel. The temperature of the cooling water is specified in the cheek area. The electrode goes through all stages of phase transformations gradually.

During operation the metal hood and ribs are burned out while a certain temperature is reached. there are no hood and ribs in the carbonization zone block.

The method of elementary heat balances as a solution of the calculation problem of temperature fields of the electrode is used [8]. For that the simulated section of the electrode is divided into annular (cylindrical) elements along the radius (index i) and height (index k) of the electrode. For an arbitrary i, k-th element, the heat balance equation can be written as:

$$
\Delta Q_{i+1,k} + \Delta Q_{i,k+1} + \Delta Q_{i-1,k} + 
\Delta Q_{i,k-1} + \Delta Q_V = \Delta Q_{\tau+\Delta \tau}, \quad (1)
$$

Fig. A typical electrode column:
L1 – the zone of the charge; L2 – free zone; L3 – cheek area; L4 – the mantel zone; A – the loading zone; Q_i – heat fluxes of electrode

The current density in the cheeks is unequal along the height of the cheeks and in the zone of the charge due to the spreading of current into the charge from the side surface of the electrodes.

During working operation the end of the electrode burns out and takes a parabolic shape which makes it necessary to shift down the electrode for a certain length. Moving down is made periodically.

The electrode baking takes place due to Joule’s Heat and heat from the smelting bath. The electrode...
the gas is specified in the free zone and it is a function of height and time. The temperature of the charge layer adjacent to the electrode and the temperature of the surface of the working end of the Electrode are specified in the charge zone.

For calculation the Joule’s Heat that released in the electrode during passaging of electric current, the current density is determined at every calculated point. Assuming that the current lines are directed parallel to the electrode axis, then the distribution of the current density over the cross section of the electrode can be determined from the equation for a cylindrical wire of circular cross section.

\[ \delta = \delta_{m0} \cdot I_0(x), \tag{3} \]

Here \( \delta_{m0} \) is the complex amplitude of the current density along the axis of the wire;

\[ I_0(x) = 1 - \frac{x^2}{r^2} + \frac{x^4}{(2 \cdot 4 \cdot 6)} - \text{Bessel's function of the first kind of zero order}; \]

\[ x = 2 \cdot \sqrt{j \cdot \omega \cdot \mu \cdot \gamma}; \]

\[ r - \text{current radius}; \]

\[ \omega - \text{angular frequency}; \]

\[ \mu - \text{magnetic permeability}; \]

\[ \gamma - \text{specific thermal conductivity}. \]

The amount of heat released per unit time in the \( i \), \( k \)-th element can be determined from the expression:

\[ \Delta Q_{vi,k} = \delta_{i,k}^2 \cdot \sigma_{i,k} \cdot \Delta V_{i,k}, \tag{4} \]

Here \( \sigma_{i,k} \) is the specific electrical resistance;

\[ \Delta V_{i,k} - \text{volume of } i, k \text{-th element}. \]

The thermal and electrophysical dependences of the electrode mass vs temperature, phase transformations and latent heats of chemical reactions are taken into account while calculating the temperature field. The mathematical model takes into account an effect of the ribs and the hood on the distribution of electric current and Joule’s Heat over the cross section of the Electrode. In case heating ferromagnetic materials under impact of an electromagnetic field, the magnetic permeability at first decreases relatively slowly, and then dropping down sharply as a certain temperature (Curie Point) is reached. The material loses its magnetic properties completely and goes into into a paramagnetic state. Therefore there are three gaps of temperatures those characterized by significant differences in the distribution of the current over the cross section of the Electrode: from the initial temperature to the Curie Point; from the Curie Point to the burnout temperature of the hood and ribs; from the burnout temperature and up temperature; the ribs and hood are not taken into account in the calculation process at the burnout temperatures and higher.

The burning out of the working end of the Electrode does layer by layer, the process begins with surface layers. Burning simulation is carried out by successive exclusion of settlement points from the calculation scheme. The displacement is simulated by shifting the entire temperature field of the Electrode by the displacement setpoint periodically. The process of operation of the electrode is considered to be steady while the temperature field of the electrode at the moment of the \( n \)-th displacement coincides with the temperature field \( (n-1) \) of the displacement.

The initial data are entered into the program for every variant of option the temperature field of the electrode, including geometric, technological and operational factors, and thermal and electrophysical properties of the electrode too. The basic mathematical model of the self-baking electrode solves a problem of two-dimensional heat transfer. Its main disadvantages are:

a) do not taken into account differences in the thermal and electrophysical properties of the electrode too. The basic mathematical model of the self-baking electrode solves a problem of two-dimensional heat transfer. Its main disadvantages are:

b) do not taken into account the proximity factor while calculating the current distribution over the cross section of the Electrode and uneven distribution.

A mathematical model of the electrode has been developed which is devoid of these disadvantages. At that model the current flowing through the electrode-cheek contact and in the electrode is determined from a formula:

\[ I_{el} = I_{el} \cdot \left( 1 \pm \frac{1 - K_s}{1 + K_s} \right), \tag{5} \]

Here \( I_{el} \) is the nominal current of the Electrode, A;

\[ -K_s - \text{is the coefficient of symmetry of the current load of the contact jaws; the “+” sign corresponds to the calculation of the current in the sections facing the center of the furnace, and the “−” sign corresponds to the lining.} \]

The electric current flowing below the contact’s cheeks to its bottom end is determined from a formula:

\[ I_{el} = I_{el} \cdot K_n \tag{6} \]

Here \( I_{el} \) is the nominal current of the electrode, A;

\[ K_n - \text{is the ratio of the current density in the zone facing the center of the Furnace (to the lining) to the average current density in the Electrode. The coefficient } K_n \text{ is determined by the method} [6] \text{ and} \]
takes into account the influence of the proximity coefficient on the current distribution in the cross section of the electrodes for a three-phase current system.

The calculation of the temperature field of the electrode is carried out in two stages: I – with boundary conditions and currents for the parts of the electrode facing to the lining; II – with boundary conditions and currents for the parts of the electrode facing to the lining.

**Conclusion.** The goal of the work is to set the task of developing modern mathematical model of the secondary current network of the electric furnace which could improve the electrical parameters of the secondary current supply. The paper analyzes the main features of the mathematical model of the secondary network of the smelting furnace, identifies the stages of development and formulates the main assumptions and simplifications that could be accepted while creating this model.

**References**

1. Gasik M.I. Self-baking electrodes in ore-smelting furnaces / M.I. Gasik - M: Metallurgy, 1984 - 248 p.
2. Rozenberg V.L. Razrabotka matematicheskoy modelli i raschety na EVM rezchizm eksploatatsii samoobzhigayushchikhsya elektroodor ferroprivlanykh elektropechey / V.L. Rozenberg, T.G. Fridman, S.V. Bashlykov// Elektrotekhn. prom – nost'. Ser. Elektrotermiya. – 1977.– №1.-Pp.2-4.
3. Gorbenko V. I. Issledovaniye teplovykh rasyublennykh samoobzhigayushchikhsya elektroodor rudovostanovitelnykh poliye samoobzhigayushchikhsya elektroodor sudovosstanovitelnykh poliye samoobzhigayushchikhsya elektroodor / A.G. Grinshpunt, A.A. Shmukin, I.V. Gendin // Izvestiya metallurgicheskogo in – t. – M., 1982. – 20p.
4. Grinshpunt A.G. Matematicheskie modelirovaniye temperaturnykh poliye samoobzhigayushchikhsya elektroodor / A.G. Grinshpunt, A.A. Shmukin, I.V. Gendin // Izvestiya metallurgicheskogo in – t. – M., 1982. – 20p.
5. Grinshpunt A.G. Research of the operation modes of self-baking electrodes of high-power electric ore-smelting furnaces AT PJSC “Nikopol ferroalloy plant”/ A.G Grinshpunt, Yu.B. Dedov // The Fourteenth International Ferroalloys Congress. - 2015. – Pp. 358-366.
честве базовой. Оценены её достоинства и недостатки. Предложены критерии для создания более совершенной математической модели для выравнивания теплового поля электрода.

Задача расчета теплового поля решается методом элементарных тепловых балансов электрода. Для этого моделируемая область разбивается на кольцевые (цилиндрические) элементы по радиусу и высоте электрода.

Ключевые слова: математическая модель, самоспекающийся электрод, электрический ток электрода, тепловое поле.

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