

Optimal control of the dynamics of physical and chemical processes of Blending and Melting of Copper Concentrates

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Abstract—This paper presents the developed model of dynamics of the physicochemical processes of electromelting of copper concentrates, which was obtained taking into account the available a priori information, which makes allowance for the main features of an object and describes the change of the basic variables of the process state (quantitative aspects of material flows and power, the composition of charge, matte, and slag). Such a model can be used in the field of automation of technological processes in metallurgical and mechanical engineering, and manufacturing. Due to the complexities of the technological process, it was advisable to use classical methods.

Keywords—copper concentrates, dynamics, physico-chemical processes, blending, smelting, optimal control, mathematical model, technological process, charge, automation and control

I. INTRODUCTION

Since, according to the description, the technological

process itself is complex, we decided to use mathematical models to solve this problem. For the study of any system using mathematical methods, it is necessary to start with building its mathematical model. A mathematical model is a system of equations of the mathematical description that captures the essence of phenomena (physical, chemical, informational) taking place within an object for which an algorithm has been defined. In the work [1], the structure of analytical and statistical models of technological processes is determined based on the study of hydrodynamic mechanisms of the relationship of material flows in an object, conditions, and nature of the processes of mass–heat transfer, the kinetics of physical and chemical transformations of substances; it is implemented by the system of equations of matter and thermal balances of the process with differential or finite constraints between variables.

Based on the study of the published data on slag and matte systems, as well as the data on the operation of industrial units, it is common to use experimental and statistical methods and Arrhenius equations for modeling. It is quite difficult to select the formula of a relationship. This task is in practice based on a priori theoretical analysis of the phenomenon under study and the choice of known types of mathematical models. They

are used in the case where it is impossible to compile a determinate model, since the investigated process of blending and electrofusion is very complicated. In the work [2], the necessary stages of building of polynomial models are: collecting data on the normal operation of the facility, statistical analysis and data pre-processing, and evaluation of model structure and parameters.

An important problem of scientific and technical progress in the automation of technological processes is the development and implementation of high-quality, compact technological processes ensuring the comprehensive use of raw materials and reduction of atmospheric emissions. The following processes belong to copper production technologies: blending, melting, converting, and refining of copper. The melting process of copper is the main in the non-ferrous metallurgy.

In the work [3], choosing the optimal conditions for carrying out the above-mentioned technological processes has a significant effect on the technical and economic performance of copper melting production, i.e. reduction of energy use, improvement of the quality of the product and reduction of the cost of manufactured product. Different modeling methods are developed and used to improve the quality of technological processes, e.g. fuzzy logic could be applied for the stabilization of copper concentrates melting temperature. The work [4], describes the physico-chemical transformations and the properties of the mattes and slags of ore-thermal furnaces. The distribution pattern of electric and temperature fields in an electric furnace obtained by mathematical modeling is also given.

The work is aimed at building a model of the dynamics of physical and chemical processes of electromelting of copper concentrates.

II. MATERIALS AND METHODS

Physico-chemical mechanism of the process of electromelting of copper concentrates. Our model is based on daily observation and recording of input and output variables of the process. Among the input variables were the number of chemical compositions of loaded pellets, flux recycles, the amount of converter slag, and electric power. The output variables included the quantity and chemical composition of the matte, waste slag, waste gas, and energy consumption.

To create a mathematical model of the melting process it is necessary to accept a system of assumptions on account of which the model will be built. In the works [5], [6], the set of stoichiometric equations describing the process of electromelting was obtained based on the results of a human-machine procedure and encompasses the dynamics of the process, while the modeling of simultaneously proceeding reactions through the system of algebraic equations is based on the priority of reactions, which is selected based on thermodynamic laws.

In the work [7], the Physico-chemical transformation of charge material and the formation of fusion products occur mainly in the furnace bath on the surface of the charge

immersed in the slag. Convection currents of superheated slag, coming in contact with the surface of the charge, pass the excessive heat to the charge and heat it to the matte and slag melting temperature. When the charge is heated to 1200 °C the processes of thermal decomposition of complex sulfides, sulfates, carbonates, and hydroxides occur. These processes result in simplifying the composition of the charge – simpler and more stable compounds are formed. Along with the processes of thermal decomposition of complex compounds by heating the charge to 1200 °C, there are processes of interaction between different chemical compounds of the charge, the most important of which are the reactions between sulfides and oxides. When the temperature of the charge is raised to 1200 – 1400°C, these processes actively progress. Sulfides of copper and iron melt and dissolve in one another, thus forming the matte (primary product of melting). The precious metals also dissolve in matte. The amount of matte expressed as the percentage to the weight of the melted solid charge depends on the amount of sulfur in the charge and the degree of desulfurization (the ratio of the sulfur mass loss during melting to its initial mass in the charge during melting expressed in percent). The more sulfur is in the charge, the greater the matte output. During electromelting the extraction of copper into matte (the ratio of the amount of metal transferred into this melting product to the amount of metal contained in the initial charge) is about 96 - 97 %.

During ore melting the basic physical and chemical transformations take place in the slag bath: its heat is accounted for the charge melt, the formation of slag and matte, and their separation. Charge gangue oxides and flux recycle transfer to the slag, their total amount is about 97 – 98 %. The slag amount is about 70 – 100 % of the charge weight. The specific heat of the slag is determined by the heat capacities of its components. Viscosity is a measure of the settling of the slag from the matte, the slag tapping from the furnace, and the heat transfer in the bath. The electrical conductivity determines the electrical mode of the electrofusion process. The electrical conductivity is determined by the chemical composition of the slag and its temperature. In the work [8], the temperature of the matte released from an ore-thermal furnace, assuming the slag temperature is known, can be estimated more or less accurately based on practical data on the temperature differential between slag and matte. In the model the heat of most endothermic reactions significantly contributed to the energy of melting, in general, is determined by a known method using the enthalpy of formation of the given compounds at the process temperature.

In our case, we used linear and nonlinear models.

In the works [9], [10], based on the analysis of the physicochemical mechanism of the process, in building a mathematical model we can distinguish the following areas (zones) in the working space of the furnace characterized by the nature of heat-mass-exchange processes:

- I – the zone of heating material and decomposition of higher sulfides, sulphates, carbonates, etc.

- II – the zone of charge melting and fundamental chemical transformations.
- III – the slag bath zone.
- IV – the matte bath zone.

Basic physical and chemical transformations occur in the slag layer of the bath. The structure of the mathematical model of such a complex metallurgical process as electrofusion may be determined by allocation of separate homogeneous zones in a furnace with appropriate boundary conditions and by obtaining of equations of connection between the zones.

The first zone of material heating and decomposition of higher sulfides, sulfates, carbonates represents a charge layer in the form of slopes on the surface of the melt.

1. The decomposition reaction is fully completed in the considered zone (zone I).
2. Heat fluxes at the zone boundaries are quasi-stationary.
3. The decomposition of sulfates and other compounds is neglected because of their small number.

Fig. 1 shows these zones.

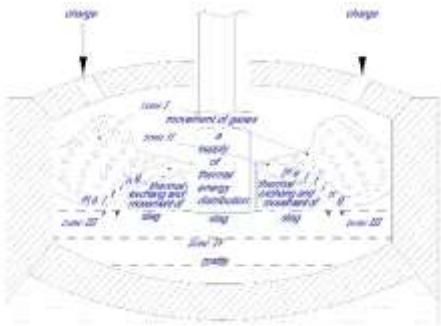


Fig. 1 Scheme of heat transfer processes in an electric furnace

The material balance equation concerning solid matter is the following equation 1:

$$\frac{dG_e^I}{d\tau} = G_{ch} - \sum_{j=1}^k a_j v_j^I - \phi_e^I \quad (1)$$

where: G_e^I is the amount of solid matter in zone I, G_{ch} is the amount of melted charge, a_j is the index of heat loss with gases, v_j^I is the velocity of substance formation in zone I as a result of the j -th reaction, ϕ_e^I is the amount of the solid matter in zone I, τ is time equation 2.

$$\frac{dG_e^{II}}{d\tau} = G_{ch} - \sum_{j=1}^k a_j v_j^I - \phi_e^I \quad (2)$$

where: G_e^{II} is the amount of solid matter in zone II.

The material balance equation concerning gaseous substance is as follows equation 3:

$$\frac{dG_r^{I-II}}{d\tau} = \phi_r^{II} - \sigma \sum_{j=1}^k a_j v_j^I - \phi_r^I \quad (3)$$

where: G_r^{I-II} is the amount of fluxing material in zones I and II, ϕ_r^I , ϕ_r^{II} are the amounts of the gaseous substance,

transferring from zones 1 and 2, relatively, σ is the thickness of charge layer.

The heat-balance equation is equation 4:

$$(G^{I-IV} C_{ch}) \frac{dT^I}{d\tau} = G_{ch} C_{ch} T_{ch} - \sum_{j=1}^k b q_j^I v_j^I - \phi_e^I C_{ch} T^I + \lambda_{ch} F (T^{II} - T^{IV}) - a_r F (T^{IV} - T_r) \quad (4)$$

where: G^{I-IV} is the amount of fluxing material in zones I-IV, C_{ch} is the charge thermal capacity, T_{ch} is the charge temperature, T^I , T^{II} , T^{IV} are the temperatures in zones I, II, IV, relatively, b is the index determining the copper content in the substances involved, q_{ij} is the heat flux at bottom of the furnace, λ_{ch} is the heat transfer coefficient of the charge, F is the area of the charge, a_r is the slag-forming substance removal coefficient, T_r is the temperature of the molten slag, where the conversion of electrical energy takes place.

The material balance equation concerning solid matter is equation 5:

$$\frac{dG_e^n}{d\tau} = \phi_e^{n-1} - \sum_{j=1}^k a_j v_j^I - v_{ml} \quad (5)$$

where: G_e^n is the charge total amount, ϕ_e^{n-1} is the amount of the solid substance, n is the number of the region ($n=1, 2, \dots$), v_{ml} is the velocity of charge melting.

The material balance equation concerning gaseous substance is equation 6:

$$\frac{dG_r^{IV}}{d\tau} = -\phi_r^{n-1} + \sigma \sum_{j=1}^k a_j v_j^n \quad (6)$$

where: G_r^{IV} is the amount of fluxing material in zone IV, ϕ_r^{n-1} is the amount of the gaseous substance, v_{nj} is the velocity of the formation of substance in the i -th part as a result of the j -th reaction.

Thus, the structure of the mathematical model of zone I that reflects the chemism of the process and consists of the kinetics equation and equation of material and heat balances can be represented by the following equation 7:

$$\frac{dG^i CaCO_3}{d\tau} = G_{CaCO_3}^{i-1} - 2K_4 G_{CaCO_3}^i - G_{CaCO_3}^{i+1} \quad (7)$$

3. Chemical reactions occur in the molten state and are described by equations of homogenous reaction.

4. The outflow of substances from a zone is proportional to their amount in the zone.

The rate of reaction in the melt will be expressed in the general form equation 8:

$$v_j^I = K_j \prod_{j=1}^8 G_{ij} \quad (8)$$

where: G_i , G_j is the weighted amount of the i -th and the j -th substances, K_j is the rate constant of the j -th reaction, whose dependence on the temperature is described by Arrhenius equation.

Then the material balance equations for the i -th substance for the zone of melting and fundamental chemical transformations can be written as follows equation 9:

$$\frac{dG_i}{d\tau} = \gamma_i^{ch} v_{ml} + \sum_{j=1}^K a_j v_j^I - a_r G_i \quad (9)$$

where: G_i is the weighted amount of the i -th substance, γ_i^{ch} is the content of the i -th substance in the charge about the reactions of decomposition of higher sulfides, sulphates, and carbonates in the zone I equation 10.

$$v_{ml} = \frac{dG^n}{d\tau} \quad (10)$$

When generating the heat balance equation for zone II it was taken into account that in the zone there takes place the melting of the charge with the hot slag flowing from zone III as a result of free convection, so the following assumptions have been made:

1. Melting occurs in the layer of the charge lowered into the melt.
2. The melting of the charge is considered a process of melting of a semi-infinite body with continuous removal of the melt from the surface.

Thus, taking into account the abovementioned assumptions, the equation of thermal balance of zone II can be written as equation 11:

$$G_r^{II} G_i^P \frac{dG}{d\tau} = \phi_e^I C_{ch} (t_{ch} - t_{ml}) + \sum_{j=1}^k (G_{iexo} q_{iexo}) - \sum_{j=1}^k (G_{iendo} q_{iendo}) - \frac{\lambda_{ch}}{\sigma} F_{ch} (t_{ml} - t_{ch}) - v_{ml} q_j^I - \sum_{j=1}^k a_r G_{ch} C_{ch} t_{ml} \quad (11)$$

where: G_r^{II} is the amount of fluxing material in zone II, G_i^P is the weighted amount of the i th substance, t_{ch} is the charge temperature, t_{ml} is the melting point, G_{iexo} is the amount of the i th substances taking part in exothermic reactions, q_{iendo} is the stoichiometric coefficient of endothermic reactions, G_{iendo} is the amount of the i th substances taking part in endothermic reactions, q_{iexo} is the stoichiometric coefficient of exothermic reactions, F_{ch} is the surface area of the melted slopes.

The temperature in zone II is taken constant and even (stationary regime), i.e. all the excessive heat is consumed for the melting of the charge.

The melting products resulted from melting and physico-chemical transformations of the charge are put into zone III, that is, into the slag bath where the heat emission and separation of slag and matte takes place (zone III), and further,

as a result of deposition sulfide materials are put into the matte bath zone (zone IV).

Thus, the mathematical model of the dynamics of physical and chemical processes occurring in electric furnace zones III and IV, which reflects the relationship between the chemism of the process, kinetics equations, equations of material and thermal balances, is represented by the following system of equation 12:

$$\begin{cases} \frac{dG_{FeO}^{III}}{d\tau} = \gamma_{FeO} v_{bl} + \frac{\mu_{FeO}}{\mu_{FeS}} K_6 G_{FeS} G_{CuO} + \\ + \frac{\mu_{FeO}}{\mu_{FeS}} K_7 G_{FeS} G_{Cu_2O} - 2 \frac{\mu_{FeO}}{\mu_{SiO_2}} K_{11} G_{FeO} G_{SiO_2} - \\ - \alpha_{FeO} G_{FeO} - \alpha_{Fe_2O_3} G_{Fe_2O_3} \\ \frac{dG_{Fe_2O_3}^{IV}}{d\tau} = \gamma_{Fe_2O_3} v_{bl} - 10 \frac{\mu_{Fe_2O_3}}{\mu_{FeS}} K_9 G_{FeS} G_{Fe_2O_3} - \alpha_{Fe_2O_3} G_{Fe_2O_3} \end{cases} \quad (12)$$

where: G^{III} is the amount of the charge in zone III of the furnace, G^{IV} is amount of the charge in zone IV of the furnace, K_j are the chemical reaction rate constants, μ is the molecular weight of the i -th substance, γ is the content of the i -th substance in the charge, α is the proportionality factor of the i -th substance removal from the zone.

The received system of equations (12) represents the structure of the mathematical model of zone III (the slag bath) and zone IV (the matte bath).

The structure of the mathematical model of zones III and IV is developed about physico-chemical, hydrodynamic, and heat regularities of the process. The physical aspects of the process taking place in the zones studied can be presented as follows.

III. RESULTS

The main products of melting, matte, and slag, formed in the zone of melting and physico-chemical transformations of the charge, pass to the zone of the slag bath. Besides, the liquid converter slag is poured into the furnace in this zone. The process of separating matte and slag is connected with the deposition of molten matte particles in the slag layer of the bath. The quality of this process depends on the difference in specific weights of materials, the viscosity of slag, melt temperature, etc. These factors to a large extent determine the loss of valuable metals with slags. Losses of copper with slags are also influenced by the processes of dissolution and oxidation of sulfides. The heat energy required for the process of ore electromelting is released in the slag bath (zone III) of the furnace as a result of active resistance to electrical current.

Multifactor correlation and regression analysis have been carried out. It helped to substantiate the interrelationship of the factors affecting specific energy consumption. Using the known formulae for calculation of mathematical expectations, dispersions of values, and pairwise correlation coefficients we have computed the indicators necessary to find the coefficients of the regression equation. In the heat balance of the melting the main parameter is the heat carried away by-products of melting: slag, matte, gas, and heat for melting and overheating

of matte and slag.

When the composition of the charge and the contents of the charge components are known, we can calculate the material balance of the electromelting. During calculating the heat balance it is necessary to calculate the heat brought into the furnace by raw materials and the heat formed during the exothermic chemical reactions.

Then we calculate the heat emanated from the furnace with the chemical substances, lost through the refractory lining and the furnace casing, and absorbed by endothermic reactions. Knowing the thermodynamic functions of chemical substances it is possible to calculate the thermal effects of chemical reactions. It should be noted that at the negative value of enthalpy heat is released, i.e. the reaction is exothermic; at the positive value of enthalpy it is endothermic.

IV. DISCUSSION

There are statistical models whose construction is based on experimental and statistical methods of studying an object and processing the observation data. They are of great interest about structural changes for obtaining a model of electromelting process control. The required steps of model building are the following: collecting of data about the normal functioning of the facility, statistical analysis and data pre-processing, and evaluation of model structure and parameters.

System of equations (11) represents the mathematical model that describes the main physicochemical and thermal transformations taking place in the studied zones of the process of electromelting of copper concentrates.

Furthermore, due to the complexity of research of the process of electromelting of copper concentrates in industrial conditions, the developed mathematical model of the process belongs to the class of epistemological models. We foresee that this model can be used in the study of the process, identifying regularities and the effect of various input factors on output parameters of blending and melting of copper concentrates, as proved by the obtained results. The results allow us to substantiate the possibility of using this model for automated systems of control of production processes.

V. CONCLUSION

Since the technological process itself is complex and continuous we mathematically described the dynamics of the process of blending and electromelting of copper concentrates concerning the systemic relations of the process of the copper melting industry. To simplify the mathematical description of the process of electromelting, the furnace is divided into four zones: the zone of material heating and decomposition of higher sulphides; the zone of melting and fundamental chemical transformations; the zone of slag bath, and the zone of matte bath. Based on a generalization of the published data on physico-chemical regularities and theoretical studies of the process of electromelting of copper concentrates the structure of a basic mathematical model of the process was built. The model, which was built taking into account the kinetics of chemical reactions, processes of mass, and heat transfer of

interacting substances, can be used in the field of automation of technological processes and production in metallurgical and mechanical engineering, manufacturing.

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Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

Aliya Kalizhanova conducted an organizational moment for an optimal control of the dynamics of physical and chemical processes of Blending and Melting of Copper Concentrates.

Aliya Kalizhanova, Ulzhan Imanbekova, Ainur Kozbakova investigated the process and also developed a mathematical model described in the section.

Aliya Kalizhanova, Ulzhan Imanbekova, Aliya Imanbekova, Anar Utegenova carried out the simulation and the optimization.

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Conflicts of Interest

The authors have no conflict of interest to declare that is relevant to the content of this article.

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