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PARAMETRIC IDENTIFICATION OF A MATHEMATICAL MODEL FOR THE COPPER MATTE CONVERSION PROCESS

Abstract. The paper provides data on the construction of mathematical models using parametric identification of objects, as well as the development of algorithms that allow calculating optimal charge plans in production, and also addresses issues related to modeling and control of electric melting. As a result of the work, the issues of partial automation through channels have been solved: regulation of electric power, charge loading control, melt level measurement, research on mechanization and automation of smelting products, as well as theoretical, experimental and pilot industrial studies on automation of electric furnaces of non-ferrous metallurgy. This control system of the electrothermal furnace operates in open mode, solves individual functional tasks of process control and management and provides solutions to the problems of optimal control of the technological process of electric melting. The paper also discusses issues related to the automatic control of the electric power of electrothermal furnaces. The furnace is considered as an object of channel control: electrode deepening-electrode currents.

Keywords. Processing of copper raw materials, blending, smelting, parametric identification.

Introduction.

Currently, a number of simplified models of electric melting with idealization of various types have been proposed, reflecting certain processes occurring in an electrothermal furnace. The mathematical model is based on the relations of thermodynamics of irreversible processes, the theory of transfer of matter and energy. The analysis and mathematical description of the processes are based on the Onzager equations. Here, the controlled object is considered by analyzing the general properties of an electrothermal furnace as an energy and substance converter [1].

These works are devoted to the issues of mixing and development of technical means for batch dosing systems. As well as issues of control and automatic regulation are considered in these [2] works.

The complex of technological processes of the metallurgical workshop is characterized by a sequential connection of sections with parallel operation of the same type of units, bypass and disposal and represents a structurally complex technological scheme [3].

Operational management of the complex of technological processes is aimed at ensuring the rhythmicity of production, provided that the plan for the production of rough copper is fulfilled in conditions of random external and internal disturbances of the drift of qualitative and quantitative characteristics of basic and auxiliary materials, changes in planned tasks, the state of individual and technological units, the experience and skills of shift personnel.

Materials and methods.

Due to significant interference in measuring the variables of the ore-thermal electric melting process and a limited number of observations based on which the mathematical model was established, confidence intervals of the model parameters were constructed according to, which showed sufficient accuracy of their estimates.

The study of the sequence of estimates of individual coefficients of dependencies I/IV obtained by virtue of the algorithm showed that the sequences of estimates are not set at the limit level despite the fact that the number of observations (steps of the algorithm), starting from a certain one, exceeds a sufficient number of observations to calculate the parameters of these equations according to.

This pattern can be explained by the manifestation of non-stationary properties of the identified object. Under these conditions, it becomes necessary to adapt the model, i.e. to obtain current estimates of its parameters as the characteristics of the object drift.

The effectiveness of using the adaptation algorithm in identification tasks largely depends on the conditions of its operation – a combination of factors such as the degree of noise of object variables, the dimension of the desired parameter vector, the degree of correlation of input variables.

The implementation of the adaptation algorithm of the mathematical model is carried out as one of the blocks of the algorithm for optimal control of the technological process of electric melting, defines strict requirements for the object of machine memory occupied by the adaptation algorithm, its complexity, speed, accuracy. Currently, the application and expansion of the use of electronic computing technology in non-ferrous metallurgy makes it possible to solve the issues of creating effective control and management systems [4]. Situational management methods make it possible to create a mathematical description of complex objects in the language of semiotic models, which significantly reduces the amount of calculations when solving management problems [5].

The use of CVM in the charging processes makes it possible to solve the problems of optimal choice of the proportion between the materials being charged, realizing a given chemical composition of the charge, forming them in the form of mathematical programming [6]. The formulation of such tasks is determined by the relationship between the number of materials to be mixed – M and the number of regulated components of the chemical composition of the mixture – N.

The problem of minimizing flux consumption at M>N was solved in relation to the preparation of a charge for lead production. In [7], the formulation of the optimal mixing problem for M<N is proposed.

Unlike traditional methods of charge calculation, it is proposed to calculate the optimal composition of the charge using the method of the planned experiment with a steep descent to the optimum. The cost per ton of copper in matte, consisting of the cost of fuel and fluxes, was taken as the target function [8]. As a result, the following linear model was obtained:

$$Y=8{,}74-10.15X_1+0.22X_2.$$

where X_1 is the quartz consumption;

X_2 is the consumption of limestone.

The equation of the copper content depending on the composition of the slag is as follows:

$$Cu=3{,}455-0{,}1475SiO_2+0{,}001683(SiO_2)^2,$$

where Cu, SiO_2 are, respectively, the contents of copper and silica in the dump slag.

However, the proposal of formulation and calculation does not solve the problem of a formalized choice of requirements for the composition of the charge, limiting the range of acceptable solutions to the mixing problem [9]. In conditions where the costs and chemical compositions of individual charge materials are random, the results of the work are directly irreplaceable for practical use with optimal control of the process of electric melting of copper concentrates [10]. The method of charge calculation developed by us is based on a mathematical model of the process describing the interrelationships of variable melting processes, adjusted as data on the process becomes available. The calculation of the charge is reduced to solving a system of linear equations and does not solve the problem of optimal charging [11].

The charge preparation control system performs continuous measurement of chemical compositions and weighing of the charged materials and, based on these data, controls the dosing of the charge components, their mixing, humidification, and transportation [12]. The use of a mathematical model of the charge preparation process in the system in the form of a system of differential equations allows for high accuracy in maintaining a given chemical composition of the charge in both static and dynamic modes of operation of the units, as well as data on solving the problem of optimal charge preparation.

The collection of experimental data is carried out with round-the-clock shift monitoring of the progress of the implementation of melting schedules in the converter department. In the course of the research, the following was carried out:

a) timing of the process operations on all working converters (the time of the beginning and end of purges, slag discharge, black copper spill, etc. were recorded);

b) determination of the average flow rate and the amount of blast applied per purge (processing records on diagram tapes), determination of the amount of ore to be loaded (time of operation of the dispenser), determination the amount of loaded matte, cold materials, drained slag (visually, according to the control department);

c) determination of the chemical composition of matte *(%Cu)*, ore *(%SiO2*, converter slag *(%Cu,*SiO_2), (according to the control department);

d) fixing the reasons for the deviation of the process from the melting schedule.

During the period of experimental studies, data on 75 converter melts were obtained. Based on the processing of experimental data and records in the observation log, it was established:

1) with a total deviation of the melting time from the set one of less than 30 minutes, 8 heats (11%) were performed, 32 heats (44%) less than 1 hour, and 33 heats (15%) more than 1 hour.

Results.

In an electrothermal furnace, it is necessary to measure the electrical conductivity of the bath *G* (static conductivity) and the derivative of this conductivity $\frac{dG}{d\mu}$, which require the introduction of information sources inside the process. necessary (1), (2) and sufficient (3) conditions for the optimality of the melting process in an electrothermal electric furnace have been obtained the following Equations 1-3.

$$G = const, \quad (1)$$

$$\frac{dG}{Gd\mu} = const, \quad (2)$$

$$k_e = \frac{dG}{Gd\mu} = min. \quad (3)$$

Where μ is the relative penetration of the electrode into the melt, the following Equations 4:

$$\mu = \frac{h_e}{H}, \quad (4)$$

where h_e is the penetration of the electrodes into the melt;

H is the total height of the furnace bath.

The proposed method of process optimization is not complete enough, because the problem of optimizing the composition of the charge and the technological regime is not solved from the point of view of minimizing losses of valuable metals with slags, and is also used for ore-thermal furnaces with a low height of the slag bath (up to 1 m), whereas the height of the slag bath of modern furnaces for smelting copper ores reaches 1.5-1.7 m .

In addition, the practical implementation of the method is complicated by the need to determine the derivative $\frac{dG}{Gd\mu}$, which is practically impossible under interference conditions. The model is based on a mathematical description consisting of differential equations of kinetics, material and thermal balance of the process. The developed model with a sufficient degree of accuracy can serve as a source of information about such process variables as the concentration of carbon and zinc in the reduction zone, the concentration of CO и CO_2 in gases leaving the layer, and the temperature of the reduction zone.

The model solves a particular problem of describing the process of electrothermal reduction of Z_n in a solid layer. We set ourselves the task of considering the processes occurring in a slag bath. Using this mathematical model in the control system for electric melting of copper concentrates is difficult due to the much larger number of components involved in physico-chemical transformations in the furnace bath during electric copper melting, as well as the need to describe their changes during the process. The automated control system includes: a system for loading the charge into the furnace, measuring the level of slag and matte, an automatic power control system that ensures the stabilization of electrical power and switching voltage levels. Here we also describe the synthesis of a high-speed automatic furnace power control system, taking into account the mutual influences of electrode currents, which provides compensation for the deterministic component of current regime disturbances, that is, a mathematical model of the furnace is given along the studied channel.

The process of melting copper concentrates is controlled using a PC, the system is based on a mathematical model of the process and works in real time. It controls the temperature regime (120 points), pressure (30 points), air flow (30 points), melt level in the furnace (20 points), charge melting and controls these parameters. This system, based on dynamic optimization, manages the processes of reflective and converter melting. The system allows you to automatically change the setpoints, constantly maintaining the optimal operating mode of the furnace, here the methodological and algorithmic security of the developed systems is highlighted, which allows them to be used in the development of a control system for the process of electric melting of copper concentrates.

The variable tasks are indicators of the current state of each converter (1st period, 2nd melting period or stop at the end of melting / respectively X_{ijk}, $Y_{ijk} Z_{ijk}$),), as well as the weights of individual smelts S_{ij}, here, the following Equation 5:

$$\overline{\imath = 1, m; \jmath = \overline{\overline{0, n; K = \overline{1, N}}}}. \tag{5}$$

Variables take integer values - the status indicator is assigned 1, if the j-th melting in the i-th converter is in the corresponding state during the k-th time interval, S_{ij} is the number of buckets loaded into the i-th matte converter for the j-th melting.

The optimal solution of this problem is assumed in the sense of:

a) the requirement of uniform supply of sulfur dioxide to sulfuric acid production the following Equation 6:

$$F_1 = \sum_{K=1}^{N} \left(\sum_{j=1}^{n} \sum_{i=1}^{m} Y_{ijK}\right)^2 \longrightarrow \min \tag{6}$$

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b) minimum waiting time requirements for loading rough copper into the anode furnace the following Equation 7:

$$F_2 = \sum_{\xi=1} \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{K=1}^{K_2} z_{ijK} \longrightarrow \min \quad (7)$$

where $K_\xi, \xi = 0, æ$ - are the column numbers of the Gantt table corresponding to the beginning of the 1st period of the process in individual anode furnaces.

c) the compromise requirement furnace the following Equation 8:

$$F_3(\varepsilon_1, \varepsilon_2) = \varepsilon_1 F_1 + \varepsilon_2 F_2, \quad (8)$$

where $\varepsilon_1 \varepsilon_2$ are positive weighting coefficients amounting to one.

Under restrictions:

1. Positional constraints the following Equation 9:

$$a \le S_{ij} \le b, X_{ijK} = X_{ijK}^2 = Y_{ijK}^2, Z_{ijK} = Z_{ijK}^2 \vee_{ijK}, \quad (9)$$

where a and b are, respectively, the minimum and maximum number of stein buckets loaded into the converter.

2. The requirement to find the unit at some point in time in only one of the possible states the following Equation 10:

$$X_{ijK} + Y_{ijK} + Z_{ijK} = 1. \quad (10)$$

3. The initial state of the converter section is fixed the following Equation 11:

$$X_{ijK} = const, Y_{ijK} = const, Z_{ijK} = const \quad \forall_{i,j,K} \quad (11)$$

if $Y_{i11} = 1$, then $S_{i1} = const.$ is accepted.

4. Restriction on the daily output of rough copper the following Equation 12:

$$\alpha \sum_{i=1}^{m} \sum_{j=1}^{n} S_{ij} \ge G_{Cu}^{plan}, \quad (12)$$

where G_{Cu}^{plan} is the plan for the production of rough copper, i.e.;

α is the conversion factor.

Discussion.

5. Limitation of converter downtime between melts the following Equation 13:

$$t_{ij}^{z} = \Delta T \sum_{K=1}^{N} Z_{ijK} \ge t_{serv}. \quad (13)$$

Here $\Delta T = \frac{1440}{N}$ – is the length of a separate time interval in the Gantt table, min.;

t_{serv} - is the maintenance time of the converter in the period between melts.

6. Limitation on the duration of the 1st and 2nd melting period the following Equations 14-15:

$$t_{ij}^{X} = \Delta T \sum_{K=1}^{n} X_{ijK} = S_{ij} \gamma_1; \quad (14)$$

$$t_{ij}^{X} = \Delta T \sum_{K=1}^{N} Y_{ijK} = S_{ij} \gamma_2 \quad (15)$$

here γ_1 and γ_2 are the coefficients that establish the dependence of the duration of the 1st and 2nd conversion periods on the copper content in the matte, the intensity of the air blast, the oxygen content in the blast and the weight of the 1st matte bucket.

7. The requirement of continuity of each melting period following Equations 16-17:

$$t_{ij}^{Y}(X_{ijK}\text{-}X_{ijK=1}\text{-}1)\text{-}\ \Delta T\sum_{v=K+2}^{N} X_{ijv}\leq 0: \quad (16)$$
$$t_{ij}^{Y}(Y_{ijK}\text{-}Y_{ijK+1}\text{-}1)\text{-}\ \Delta T\sum_{v=K+2}^{N} Y_{ijv}\leq 0. \quad (17)$$

The requirement of each unit according to the scheme is the 1st period, the i-th melting is the 2nd period; the i-th melting is simple after the i-th melting is the 1st period of i+1st melting, etc. following Equations 18-20:

$$t_{ijK}^{X}\, Y_{ijK}\leq \Delta T\sum_{v=1}^{K-1} X_{ijv}; \quad (18)$$
$$t_{ijK}^{Y}\, Z_{ijK}\leq \Delta T\sum_{v=1}^{K-1} Y_{ijv}\ ; \quad (19)$$
$$t_{ijK}^{Z}\, Z_{ijK}\leq \Delta T\sum_{v=1}^{K-1} Z_{ijv}. \quad (20)$$

The criterion of optimality of the technological regime is introduced and its connection with the main parameters of electrothermal melting, static and dynamic conductivity of the melt, which are directly measured during the operation of the furnace by the magnitude of its external flows and forces, is established. A general criterion for the optimality of the electric melting process is obtained in the form of a condition for a minimum ratio of the increase in dynamic and static conductivity through the energy channel.

Conclusion.

Control and control systems for technological processes of charge preparation and electric melting both in the Republic of Kazakhstan and abroad perform the tasks of partial disparate local control and regulation of individual variables. The paper solves the problem of developing a method and a system for optimal automatic control of an electric furnace for ore-thermal smelting of copper raw materials. As a result of the implementation of this system, the productivity of the units has increased, power consumption has decreased and the number of maintenance personnel has decreased. In this paper, a mathematical model is constructed using parametric identification of control objects. All research on the creation of automated control systems for technological processes of electric melting in the copper industry was carried out with the use of computer technology. The control system for the technological process of electric smelting of copper ores and concentrates has been tested in industrial conditions.

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REFERENCES*

[1] Malfliet A., Lotfian S., Scheunis L., Petkov V., Pandelaers L., Jones P.T., Blanpain B. Degradation mechanisms and use of refractory linings in copper production processes: Journal of the European Ceramic Society. A critical review. 34, 3 (2014), p. 849-876.

[2] Kim B.S., Jo S.K., Shin D., Lee J.Ch., Jeong S.B. A physico-chemical separation process for upgrading iron from waste copper slag. International Journal of Mineral Processing. 124 (2013), 124-127.

[3] Cheng P., Herreros P., Lalpuria M., Grossmann I. Optimal scheduling of copper concentrate operations under uncertainty. Computers & Chemical Engineering, 140(2020), p.106919. doi.org/10.1016/j.compchemeng.2020.106919

[4] Gorai B, Jana R.K. Characteristics and utilisation of copper slag—a review. Resources, Conservation and Recycling. 39(2003) p.299-313. doi.org/10.1016/S0921-3449(02)00171-4

[5] Guimarães F.Y., Santos I.D., Dutra J.B. Direct recovery of copper from printed circuit boards (PCBs) powder concentrate by a simultaneous electroleaching–electrodeposition process. Hydrometallurgy, 149 (2014), p. 63-70.

[6] Zhai Q., Runqing Lui. Simultaneous recovery of arsenic and copper from copper smelting slag by flotation: Redistribution behavior and toxicity investigation. Journal of Cleaner Production. Volume 425, 1 November 2023, 138811

[7] Imanbekova U., Hotra O., Koshimbayev S. K., Popiel P., Tanas J. Optimal control of blending and melting of copper concentrates. Proceedings of SPIE-The International Society for Optical Engineering , (2015), 9662,966246.

[8] Rubanenko O. O., Komar V. O., Petrushenko O. Y., Smolarz A., Smailova S., Imanbekova U., Determinition of similatiry criteria in optimization tasks by means of neuro-fuzzy modelling. Journal Przegląd Elektrotechniczny, 3(2017), 93-96

[9] Hotra O.Z., Koshimbayev S.K., Imanbekova U.N. Modelling in Matlab using fuzzy logic for improving the economic factors of melting of copper concentrate charge. Actual problems of economics, 11 (2014), 380-387.

[10] Da-wei Wang, Yan-jie Liang. Comprehensive recovery of zinc, iron and copper from copper slag by co-roasting with SO2–O2. Journal of Materials Research and Technology. Volume 19, July–August 2022, Pages 2546-2555

[11] Istadi I., Bindar Y. Improved cooler design of electric arc furnace refractory in mining industry using thermal analysis modeling and simulation. Applied Thermal Engineering, 01 (2014), 1127-1138.

[12] Imanbekova U., Hotra O., Koshimbayev S., Optimal control of copper concentrate blending and melting based on intelligent systems. Journal Przegląd Elektrotechniczny, 8(2016), 125-128

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МЫС ШТЕЙНДІ ҚАЙТА ӨҢДЕУ ПРОЦЕСІНІҢ МАТЕМАТИКАЛЫҚ МОДЕЛІН ПАРАМЕТРЛІК ИДЕНТИФИКАЦИЯЛАУ

Аңдатпа. Мақалада объектілерді параметрлік сәйкестендіруді қолдана отырып, математикалық модельдерді құру, сондай-ақ өндірістегі оңтайлы жоспарларды есептеуге мүмкіндік беретін алгоритмдерді әзірлеу туралы мәліметтер келтірілген, сонымен қатар модельдеу мен электр балқытуды басқаруға қатысты мәселелер қарастырылған. Жұмыс нәтижесінде арналар бойынша ішінара автоматтандыру мәселелері шешілді: электр қуатын реттеу, шихтаның жүктемесін бақылау, балқу деңгейін өлшеу, бұйымдарды балқытуды механикаландыру және автоматтандыру бойынша зерттеулер, сондай-ақ түсті металлургия электр пештерін автоматтандыру бойынша теориялық, эксперименттік және тәжірибелік-өнеркәсіптік зерттеулер. Бұл электртермиялық пешті басқару жүйесі ашық режимде жұмыс істейді, технологиялық процесті бақылау мен басқарудың жеке функционалдық міндеттерін шешеді және электр балқытудың технологиялық процесін оңтайлы басқару мәселелерін шешуді қамтамасыз етеді. Мақалада сонымен қатар электртермиялық пештердің электр қуатын автоматты түрде реттеуге қатысты мәселелер қарастырылады. Пеш арнаны басқару объектісі ретінде қарастырылады: электродты тереңдету - электрод токтары.

Түйінді сөздер. Мыс шикізатын қайта өңдеу, араластыру, балқыту, параметрлік сәйкестендіру.

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ПАРАМЕТРИЧЕСКАЯ ИДЕНТИФИКАЦИЯ МАТЕМАТИЧЕСКОЙ МОДЕЛИ ПРОЦЕССА ПЕРЕРАБОТКИ МЕДНОГО ШТЕЙНА

Аннотация. В статье приводятся данные по построению математических моделей с использованием параметрической идентификации объектов, а также алгоритмы действии, позволяющих рассчитывать оптимальные планы шихты на производстве, а также рассматриваются вопросы, связанные с моделированием и управлением электроплавкой. В результате работы были решены вопросы частичной автоматизации по каналам: регулирование электрической мощности, контроль загрузки шихты, исследования по механизации и автоматизации выплавки изделий. В статье были рассмотрены теоретические, экспериментальные и опытно-промышленные исследования по автоматизации электропечей цветной металлургии, так как данная система управления электротермической печью работает в открытом режиме, решает индивидуальные функциональные задачи контроля и управления технологическим процессом и обеспечивает решение задач оптимального управления технологическим процессом электроплавки. Здесь же рассматриваются вопросы, связанные с автоматическим регулированием электрической мощности электротермических печей, так как печь рассматривается как объект управления каналом: углубление электрода - электродные токи.

Ключевые слова. Переобработка медного сырья, смешивание, плавка, параметрическая идентификация.

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