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DEVELOPMENT OF AN ALGORITHM FOR ADAPTING A MATHEMATICAL MODEL OF THE PROCESS OF MIXING AND MELTING COPPER CONCENTRATES

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The paper describes the information base of the system, which is formed by algorithms of centralized control, automated analytical control system and control data of material flows. The data processing algorithm according to a special program generates additional information necessary to solve the control tasks of the system and includes algorithms for processing analytical data information, as well as data for monitoring material flows, calculations of additional electric furnace variables, loading of charge into furnace bunkers and technological variables by department. The simulation model of the functioning of the complex ”technological process – control system” is implemented in the form of a package of interconnected software modules. The package implementing the simulation model is divided into three complexes: a set of programs for ”Data collection and processing”; a complex for ”Optimal process control”; a set of programs for ”optimal energy regime management”.

Keywords. Copper raw materials, blending, smelting, mathematical model, mixing and melting.

МЫС КОНЦЕНТРАТТАРЫН АРАЛАСТЫРУ ЖӘНЕ БАЛҚЫТУ ПРОЦЕСІ ҮШІН МАТЕМАТИКАЛЫҚ МОДЕЛЬДІ БЕЙІМДЕУ АЛГОРИТМІН ӘЗІРЛЕУ

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Мақалада орталықтандырылған басқару алгоритмдерімен, аналитикалық бақылаудың автоматтандырылған жүйесімен және материалдық Ағындарды бақылау деректерімен қалыптасатын жүйенің ақпараттық базасы сипатталған. Арнайы бағдарлама бойынша деректерді өңдеу алгоритмі жүйені басқару мәселелерін шешу үшін қажетті қосымша ақпаратты жасайды және аналитикалық ақпаратты өңдеу алгоритмдерін, сондай-ақ материалдық Ағындарды бақылау, электр пешінің қосымша параметрлерін есептеу, пештің бункерлеріне шихтаны жүктеу және цехтар бойынша технологиялық параметрлерді қамтиды. «Технологиялық процесс – басқару жүйесі» кешенінің жұмыс істеуінің имитациялық моделі өзара байланысты бағдарламалық модульдер пакеті түрінде іске асырылды. Модельдеу моделін жүзеге асыратын Пакет үш кешенге бөлінеді: «деректерді жинауға және өңдеуге» арналған бағдарламалар жиынтығы; «технологиялық процесті оңтайлы басқаруға» арналған кешен; «оңтайлы энергетикалық режимді басқаруға» арналған бағдарламалар жиынтығы.

Түйін сөздер: мыс шикізаты, араластыру, балқыту, математикалық модель, араластыру және балқыту.

РАЗРАБОТКА АЛГОРИТМА АДАПТАЦИИ МАТЕМАТИЧЕСКОЙ МОДЕЛИ ДЛЯ ПРОЦЕССА СМЕШИВАНИЯ И ПЛАВЛЕНИЯ МЕДНЫХ КОНЦЕНТРАТОВ

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В статье описана информационная база системы, которая формируется алгоритмами централизованного управления, автоматизированной системой аналитического контроля и данными контроля материальных потоков. Алгоритм обработки данных по специальной программе генерирует дополнительную информацию, необходимую для решения задач управления системой, и включает в себя алгоритмы обработки аналитической информации, а также данные для мониторинга материальных потоков, расчетов дополнительных параметров электропечи, загрузки шихты в бункеры печи и технологических параметров по цехам. Имитационная модель функционирования комплекса ”технологический процесс – система управления” реализована в виде пакета взаимосвязанных программных модулей. Пакет, реализующий имитационную модель, разделен на три комплекса: набор программ для ”Сбора и обработки данных”; комплекс для ”Оптимального управления технологическим процессом”; набор программ для ”управления оптимальным энергетическим режимом”.

Ключевые слова. Медное сырье, смешивание, плавка, математическая модель, смешивание и плавка.

Introduction. To predict process variables using an adaptive mathematical model, constant updated samples containing a certain number of observations of the process must be stored in the PC memory [1]. When the operator enters the code of a certain equation of the model, the corresponding values of the model parameters, object variables and algorithm constants are received at the algorithm input, the adjusted model parameters and the predicted value of the object variable are printed [2].

The analytical information processing algorithm generates information about the chemical compositions of material flows necessary for solving functional control tasks using information arrays generated by an automated analytical control system based on *X-ray* spectral equipment [3]. The data is sent to the computer of the automated control system of the metallurgical workshop via interprocessor communication channels as they are formed. The data on the chemical composition of the melting products relate to the moments of discharge of these products, which are random in nature [4]. The output information of the algorithm is preprocessed information about the chemical composition of material flows [5].

Based on the data of the daily work schedule of the electric furnace department, which determines the number of processed granules, revolutions, limestone, liquid converter slag, a given electrical power, taking into account the current chemical composition of the loaded materials, a table of initial data was filled in, which were transmitted via communication channels to the information and computing center [6]. The obtained data of the optimal technological regime were printed out and transmitted to the shift foreman in the form of a task for implementation during the process [7].

Materials and methods. During the tests, the following values characterizing the electric melting process were recorded in the observation log: date and shift number, set and actual, number of loaded materials (by type), power consumption, electric power of the furnace, current and voltage at the electrodes, the amount of matte produced, the amount of fused slag; the results of chemical analyses of the loaded materials and the products received; the surname of the replacement master; the time of solving the problem on the PC [8].

The tests were carried out in two stages: at the first, data was collected during the usual (existing) control of the electric welding process, at the second – during the implementation of the process according to the optimal control algorithm [9].

The choice of a working algorithm for adapting a

mathematical model that best satisfies the condition of accuracy of approximation by the model of the output variables of an object over a time interval of length is reduced to determining the type of operators $\psi\{.\},\{.\}$ of the sequence type $\gamma[k]$, the value of constants η, and the minimum sample length [10].

We present a working algorithm for adapting the mathematical model of electric melting.

The adaptation algorithm calculates the current values of the parameters of the mathematical model based on the initial data:

a) the current values of the output and input variables of the adapting equation (model).

b) the values of the parameters obtained at the previous step of the algorithm;

c) values of constants;

d) the calculated value of the output variable obtained at the previous step of the algorithm.

The output information of the algorithm is the adjusted values of the equation parameters to the following Equation 1.

$$\xi = \delta_0 + \sum_{i=1}^{m} \delta_i \psi_i \tag{1}$$

Minimizing the square of the mismatch between the actual (measured at the nth instant of time) value of the output variable to its calculated value to the following Equation 2.

$$\Delta\xi = (\xi[n] - \delta_0 - \sum_{i=1}^{m} \delta_i \psi_i[n])^2 \tag{2}$$

Where $\xi[n]$ is the output variable of the model, Here:

$\psi_i[n], (i = \overline{1,m})$ - input variables of the model,

n=1,2,... - discrete time,

$\delta_0, \delta_i (i = \overline{1,m})$ - equation parameters.

Calculation formulas to the following Equations 3-10:

$$\langle \frac{\delta_o[k] = \delta_o[k-1] + t[k]\gamma_o[k]\Delta\varepsilon[n,k-1]}{\delta_i[k] = \delta_i[k-1] + t[k]\gamma_i[k]\Delta\varepsilon[n,k-1]\psi_i[n]} \tag{3}$$

$$\delta_i[k] = \delta_i[k-1](i = 0,1,...), \tag{4}$$

$$\Delta\varepsilon[n,k] = \overline{\varepsilon}[n] - \breve{\varepsilon}[n,k] \tag{5}$$

$$\breve{\varepsilon}[n,k] = \delta_0[k] + \sum_{i=1}^{m} \delta_i[k]\overline{\psi}[n] \tag{6}$$

$$\overline{\varepsilon}[n] = \overline{\varepsilon}[n-1] + \frac{1}{T_\varepsilon}(\varepsilon[n] - \overline{\varepsilon}[n-1], \quad (i = \overline{1,m}) \tag{7}$$

$$\overline{\varepsilon}[n] = \overline{\varepsilon}[n-1] + \frac{1}{T_\varepsilon}(\varepsilon[n] - \overline{\varepsilon}[n-1]) \tag{8}$$

$$t[k] = 1 + r/\Delta\varepsilon[n-1,k-1] + \Delta\varepsilon[n-2,k-2] \tag{9}$$

$$\gamma_i[k] = \begin{cases} \overline{\gamma_i} = const\ if\ \eta[\gamma] = 1 \\ \dfrac{\gamma_i[0]}{S[n]}, if\eta[\gamma] = 0 \end{cases} \tag{10}$$

Where:

$S[n]$ - the number of steps of the algorithm after the next violation of the condition $\Delta\varepsilon[n,k]| \leq \Delta$.

$\overline{\psi}[n], \overline{\varepsilon}[n]$ - variables formed by sliding averaging over intervals, respectively T_i и T_ε;

$\delta_i[k], (i = \overline{0,m})$ - equation parameters corresponding to the kth step (iteration) of the

algorithm;

$\varepsilon[n.k]$ - calculated values of the output variable corresponding to time n, obtained using the parameters $\delta_i[k]$;

$\gamma_i[k], (i = \overline{0,m})$ - The iteration step is positive numbers that determine the amount of parameter correction at the kth step of the algorithm;

$t[k]$ - accelerating multiplier;

$\eta[\gamma]$ - a constant that defines the type of sequence $\gamma_i[k](k = 1, 2, ...)$;

$\Delta > 0$ - the threshold value of the misalignment of the value $\varepsilon[n]\tilde{\varepsilon}[n, k]$.

Results and discussion. The flowchart of the algorithm is described in this way:

Block 1 performs the sequential formation of arrays necessary for calculation from the total array of data.

Block 2 checks the completeness of information generation.

Block 3 checks the receipt of new analytical information.

The block diagram of the algorithm for processing analytical information in Figure 1.

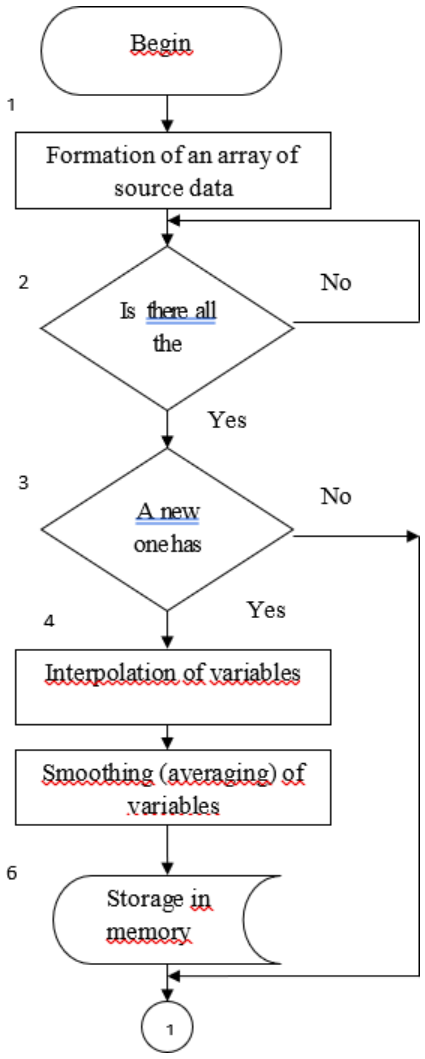

Figure 1 - The block diagram of the algorithm for processing analytical information

Block 4 calculates the interpolated value of the content of the i-th component of the j-th material of the k-th furnace to the following Equation 11:

$$X_{ijk}[n] = X_{ijk}[\mu] - \frac{\left(X_{ijk}[\mu] - X_{ijk}[\mu]\right)(n - \tau_{\mu})}{\tau_{\mu+1} - \tau_{\mu}} \quad (11)$$

Where: $X_{ijk}[\mu]$ - the content of the i-th component in the j-th material for the k-th selection furnace;

$\tau_{\mu}, \tau_{\mu+1}$- accordingly, the time of the μ and μ+1 sampling of the analyzed material

n - discrete time, the hour for which the content of the *i-th* component in the *j-th* material is determined.

Block 5 performs preliminary processing of the received information – smoothing to the following Equation 12:

$$\overline{C}[n] = \overline{C}[n-1] + \frac{1}{T}(C[n] - C[n-1]) \quad (12)$$

where $\overline{C}[n]$ - the smoothed value of the variable at the *n-th* instant of time;

$C[n]$ - the current value of the variable at the *n-th* moment in time;

T - the smoothing interval (averaging).

Block 6 stores a sequence of values of analytical variables to the following Equation 13:

$$C[n-1], i = 0, 1, 2, \ldots, N \quad (13)$$

where *N* is the memory depth. The average values of variables are stored per hour, from the beginning of the shift, per shift, from the beginning of the day, per day for each furnace.

The block diagrams of these algorithms are shown in Figure 2.

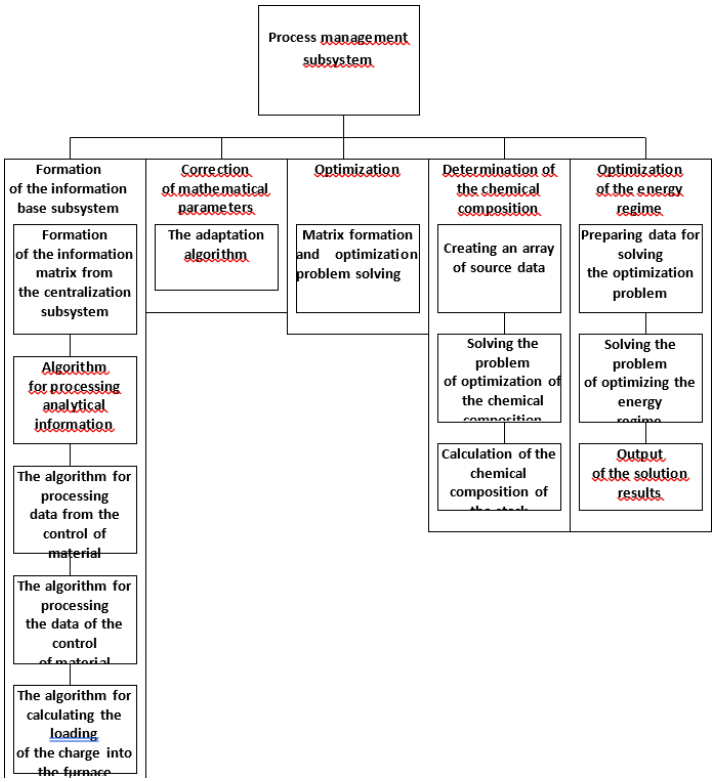

Figure 2 - The block diagrams of these algorithms

Block 1. Enters the values of these variables $X_{ij},\ Y_{ij},\ a_{ij}$ into the machine.

Block 2. Checking the values of variables for validity.

Block 3. Checking for data sufficiency, in case of insufficiency, the display unit 4 is triggered.

Block 5. The average values of the variables are found.

Block 6. The solution of equations is performed with the previous values of the coefficients, the calculated $\overline{y}\,[n]$ data are compared with the experimental $\overline{y}\,[n,K]$. $\Delta y[n,K]=\overline{y}\,[n]-\overline{y}\,[n,K]$ is calculated.

Block 7. The comparison block. If the condition $|\Delta y[n,K]|\geq\Delta$ is fulfilled, block 8 is executed, which, using block 9, leads to an adaptation, as a result of which new coefficient values are obtained.

Block 10. Calculation of the optimal composition of the charge. At the same time, we use the "Optimization" subroutine of block 11.

The algorithm for adapting the mathematical model of the process of mixing and melting copper concentrates is given below to the following Equations 14-25:

$$f_{FeS}^{III}=\alpha_{FeS}^{II-III}G_{FeS}^{II}-K_{C}G_{FeS}-K_{mech}G_{FeS}^{III}-\alpha_{FeS}^{III-IV}\frac{\vartheta_{K}}{H_{sl}}=0 \tag{14}$$

$$f_{Cu_2S}^{II}=\alpha_{Cu_2s}^{II-III}G_{Cu_2S}^{II}-K_{C}G_{Cu_2S}-G_{Cu_2S}G_{FeO}-K_{mech}G_{Cu_2S}^{III}-\alpha_{Cu_2S}^{III-IV}G_{Cu_2s}^{III}\frac{\vartheta_{K}}{H_{sl}}=0 \tag{15}$$

$$f_{CaO}^{III}=\alpha_{CaO}^{II-III}G_{CaO}+\gamma_{CaO}^{K}G^{K}-\gamma_{CaO}G_{sl}^{m}=0 \tag{16}$$

$$f_{SO_2}^{III}=\alpha_{SiO_2}^{II-III}G_{SiO_2}^{II}+\gamma_{SiO_2}^{K}G^{K}-\gamma_{SiO_2}G_{sl}^{m}=0 \tag{17}$$

$$f_{Cao}^{II}=\alpha_{FeO}^{II-III}G_{FeO}^{II}+\gamma_{FeO}^{K}G^{K}-\gamma_{FeO}G_{sl}^{m}=0 \tag{18}$$

$$G_{sl}^{II}=\beta_1G_{Cu_2S}^{III}+\beta_2G_{Cu_2O}^{III}+\beta_3G_{cp}^{III} \tag{19}$$

$$_{sl}^{II}=\gamma_nG_{Cu}^{III} \tag{20}$$

$$F_{sl}^{II}=\rho_{sl}^{R}+k_1G_{SiO_2}+k_2G_{CaO}+k_3G_{FeO}+k_4t_{sl} \tag{21}$$

$$f_{sl}^{II}=K\rho_{sl}^{R}I^2+G_{sl\,sl}^{K}t_{sl}^{K}-\alpha(t_{sl}-t_m)_{0\,sl}F_m-\alpha(t_{sl}-t_{st})F_{st}-G_{sl\,sl}^{m}t_{sl}-\sum\alpha^{III-IV}G_eC_et_{sl}\frac{\vartheta}{_{sl}}=0 \tag{22}$$

$$f_{Cu_2S}^{III}=\frac{\alpha_{Cu_2S}^{III-IV}G_{Cu_2S}^{III}}{H_{sl}}\vartheta_{k-\beta_{Cu_2S}G_{st}^{m}}=0 \tag{23}$$

$$f_{FeS}^{II}=\frac{\alpha_{Cu_2S}^{III-IV}G_{Cu_2S}^{III}}{H_{sl}}\vartheta-\beta_{FeS}G_{st}^{m}=0 \tag{24}$$

$$f_{Fe}^{II}=(\sum_{l}\gamma_lG_{st}C)t_{sl}+\alpha(t_{sl}-t_{st})F_{st}-\lambda(\frac{t_{st}-t_{sl}}{\delta})h_{st}S_n-\frac{\lambda'}{\delta}(t_{st}-t_n)F_n=0 \tag{25}$$

The block diagram of the algorithm for optimal control of the energy regime can be described as follows:

Blocks 1-6 . Collects, processes and generates mass data.

Blocks 7-20. The equations of the mathematical model of the electric melting process are being implemented. The input of the blocks receives information about the input parameters $\overline{G}$, $\overline{H}$, $\overline{U}$, $\overline{H}$ Q_c, G_{5_p}

Block 7. The equations of the material balance of the process are implemented.

Block 8. The equations of the thermal process are calculated.

Block 9. Dependence of the resistivity of the charge and slag on the input parameters determined on the basis of a study of factory slags.

Block 10. The equation of the dependence of the height of the slag bath on the input parameters.

Block 11. Expression of the dependence of the slope depth on the input parameters.

Blocks 12-16. The resistances of the equivalent electrical circuit of the furnace are calculated as a function of the geometric parameters of the specific resistances of the slag and charge and the phase voltage.

Block 17. The dependence of the phase power on the resistance of the equivalent circuit and the phase voltage is realized.

Block 18. The dependence of the amount of matte on the input parameters is determined.

Block 19. The dependences of the copper content in the dump slag on the phase voltage and the electrode depth are realized.

Block 20. The specific consumption of electricity is determined,

Block 21. The adequacy of the mathematical model to the object is checked. In case of inadequacy, he refers to the adaptation unit.

Block 22. The parameters of the mathematical model are adjusted according to the well-known adaptation algorithm

Block 23. The optimal values of control actions are determined based on the solution of the optimization problem.

Block 24. The optimization problem is solved using the Rosenbrock method.

Block 25. The furnace operation is checked for accidents. In case of failure to fulfill one of the conditions, a voltage reduction task is issued.

Block 26. The actual voltage value is compared with the optimal one. In the case of U_{real} going beyond the area $|U - U_{opt}|\varepsilon q$, a task is given to switch voltage stages in one direction or the other.

Block 27. The actual conductivity is compared with the optimal one. In case of going beyond the area $|q_i - q_{i\ opt}|\varepsilon q$, a task is given to bypass the electrode in one direction or the other.

Block 28. The condition $I \leq I_{con}$ is checked in the case of a voltage increase task. If the condition is met, the voltage can be increased.

Block 29. The position of the electrode holder is checked. If the electrode holder is in the lowest position, a task is given to increase the voltage. If not, the control is carried out by increasing the depth of the electrode.

Block 30. It is checked whether the electrode holder is in the uppermost position. If not, the electrode rises if a voltage reduction task is issued.

Blocks 31-32. The magnitude of the control action (the number of voltage stages) is determined and information is provided on which voltage stage should be operated.

Blocks 33 - 34. An algorithm for direct control of electrode deepening is implemented.

The results of processing the data obtained during the two stages of the tests are summarized in a table. The tests showed: the adequacy of mathematical models of the process of electric melting of copper concentrates and control tasks for a real object; the effectiveness of the developed algorithms and programs for solving problems of optimal calculation of the stack composition, distribution of material flows and energy management

The used energy mode of electric melting for copper sulfide concentrates made it possible to reduce the copper content in dump slags by 0.18% (absolute) and reduce copper losses with slags by 5% (relative), increase the copper content in matte by 0.97% while

reducing electricity consumption by 1.8%.

Conclusion. Industrial tests and implementation of the electric melting process control system were carried out in the electric furnace department, pilot tests of the algorithm for controlling the process of electric melting of copper concentrates in industrial conditions were carried out.

The tests were carried out in order to: clarify the coefficients of the mathematical model; verify the adequacy of the mathematical model of control tasks; adjust algorithms and programs in industrial conditions; verify the effectiveness of the developed algorithms and programs. The tests were carried out in accordance with the program and methodology.

The results of theoretical and experimental studies on the control system for the process of electric melting of copper sulfide concentrates are the basis for the design solutions of the Institute of Information and Computational Technologies CS MSHE RK.

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