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Development of a mathematical model for a compound technological complex of vanyukov melting in order to control the material and thermal regime

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ABSTRACT
This article presents a mathematical model in the form of static equations of dependencies of input and output flows based on the equations of material and heat balance for the purposes of operational planning and control of the complex technological complex of Vanyukov melting (PV). Dynamic characteristics are presented for the purpose of controlling the thermal regime based on the technology of the developed melting process with blowing from below. As a result of the study, the developed mathematical model for controlling the smelting process when calculating the material flows of the charge will allow tracking changes in the thermal state of the smelting (by the copper content in the matte). This model can quite well describe the dynamics of the state of the process, both when establishing the impacts aimed at increasing the heating of the furnace, and at reducing its heating. Based on the equations, a computer model based on the dynamic programming method in the MATLAB software package has been developed. The scientific novelty lies in the fact that for the first time, the structure of a mathematical model has been developed that describes the processes occurring in the over-tuyere zone and the sludge zone of the smelting products.

Keywords: technological complex, control system, static model, thermal regime, cooper smelting

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Introduction

Smelting is one of the important processes in copper metallurgical production, in which copper and iron sulfides are oxidized to form molten matte and slag. Flash smelting and pool smelting are the main smelting technologies in copper production. [1]. Copper concentrates react with oxygen directly in the flash smelting process, which has the advantages of high productivity and automatic control. However, the flash-melting furnace requires fine and dry materials to allow fast reactions. As a result, feed preparation is required for a significant process, and dust levels are relatively higher. It has a limited ability to process scrap and other large copper-bearing materials. Bath melting is an alternative flash melting technology that involves reacting copper concentrate with oxygen in a molten bath. In [2], several technologies have been developed based on the principles of bath melting, including IsaSmelt/Ausmelt, Noranda/El Teniente, Vanyukov, and the recently developed Bottom Blowing Smelting (BBS) process. In the article [3], BBS technology has generated a lot of interest from the copper industry due to its unique processing features such as good feedstock adaptability, high oxygen utilization and thermal efficiency, and flexible performance. Articles [[4], [5]] say that in 2016, 13 BBS furnaces were built with a capacity of 1600 thousand tons of copper per year. Basic research, including slag thermodynamics and melt bath fluid dynamics, has been widely carried out in recent years to understand and support the new technology. Reviews [[6], [7]] summarize the development of the copper BBS, including its history, features, and related basic research. The aim of the research is to develop a mathematical model of the dependence of input and output flows based on the equations of material and heat balance for the purposes of operational planning and control of the complex technological complex of Vanyukov melting.

Experimental part

The mathematical model of the Vanyukov process, developed in the framework of this study, is supposed to be used for the purposes of operational planning and management of the technological complex.

Therefore, the mathematical model of Vanyukov melting, which is supposed to be built, is selected in the class of static models based on the equations of material and heat balance for the main components of the input and output flows (copper-containing raw materials, concentrate, coal, air, oxygen, combustion gas, matte, slag, caisson temperature, exhaust gases, melt, dust, etc., released and absorbed heat) [[8], [9]].

The general structure of the model describing the process, where the input variables are the flow rates and the chemical composition of raw materials (concentrate, coal, charge, clinker), revolutions, oxygen-air mixture blowing (OAC), volumes and composition of air, oxygen, combustible gas, etc. d. and output variables of the furnace operation: quantity and composition of output products, including [10]:

- charge and content of *Cu*, *S*i, *Mg*, *S*, etc.;
- matte and its content of *Cu*, *S*, *Zn*, *P*, etc.;
- slag and its content of CaO, SiO_2, MgO, etc.;
- exhaust gases and their content of CO, CO_2, CH_4, N_2, O_2, etc.;
- dust and the content in it of the main components of input and output materials;
- waste (in fractions of the number of components in the input materials).

The basic equation for the relationship between the output variables of the model and the input ones is:

$$G_k^i = \sum_j^n \beta_{j/k}^i \, \alpha_j^i \, G_j \quad (1),$$

where G_k^i - is the amount of the *i*-th component in the *k*-th output product;

$\beta_{j/k}^i$ - coefficient of extraction (transition) of the *i*-th component from the *j*-th input material to the *k*-th output product;

α_j^i - the content of the *i*-th component in the *j*-th input stream (material), in fractions of units;

G_j - the amount of the *j*-th input (source) material.

The general form of equation (*1*) implies the possibility of taking into account all input material flows containing the i-th component (substance), which can be understood as a chemical element (for example, copper *Cu*, carbon *C*, etc.) and a stable compound (for example, oxides of calcium, silicon, magnesium - CaO, SiO_2, MgO, respectively, etc.). The choice of components *(i*), as well as the input (*j)* and output (*k*) material flows taken into account in the model, depends on the production technology and the nature of the ongoing physical and chemical processes. In this case, one can focus on metallurgical calculations of material and heat balances, which, as a rule, sufficiently reflect the current level of understanding (knowledge) of the technological features of a particular production. As a rule, the choice of component *(i*) largely depends on the respective output product: for matte, these are copper, carbon, and alloying metals; for slag - slag-forming oxides; for exhaust gases and dust - volatile and gaseous components [11].

Recovery factors used in the model ($\beta_{j/k}^i$) are widely used in metallurgical calculations. Their value is quite constant (stable) for a well-established production technology and the required accuracy of calculations performed using a mathematical model. However, for individual components to determine their content in the output products, setting the values of recovery factors requires additional calculations or the use of other calculated ratios. So the carbon content in the matte depends on the nature of the redox processes in the furnace (oxidation or carburization) [[12], [13]].

When constructing a mathematical model of the technological regime, the requirements of the material balance must be observed as for individual components:

$$\sum_{j=1}^n \alpha_j^i G_j = \sum_{k=1}^l G_k^i$$

and by the total number of input and output material flows:

$$\sum_{j=1}^n G_j = \sum_{k=1}^l G_k$$

The process of charge preparation. Calculation of the amount and composition of the charge. In the absence of experimental data and by analogy with metallurgical calculations, we believe that copper, carbon, silicon, manganese, phosphorus, and sulfur can be considered as starting materials in the charge. After carrying out experimental studies on an operating furnace, other components of the raw materials and products of reactions occurring in the furnace can be taken into account [[14], [15]].

The general equation for determining the mass amount of components in the charge is:

$$G_{ch}^{i} = \sum_{j=1}^{n} \beta_{j/ch}^{i}\, \alpha_j^i\, G_j\,, \beta = 1$$

where j – index of initial (input) material flows – concentrates (conc1- bornite Cu_5FeS_4; conc2- chalcopyrite - $CuFeS_2$; conc3 - chalcocite - Cu_2S), fluxes (conc4 - bornite FeS_2; conc5 - quartz SiO_2; conc6 - limestone - $CaCO_3$; conc7 - magnesite $MgCO_3$)

1) The amount of copper *(Cu)* in the charge:

$$G_{ch}^{Cu}=\sum_{j=1}^{n} \alpha_j^{Cu}\, G_j = \alpha_{conc1}^{Cu} G_{conc1} + \alpha_{conc2}^{Cu} G_{conc2} + + \alpha_{conc3}^{Cu} G_{conc3} \approx \alpha_{ch}^{Cu} G_{ch}$$

Similarly, equations are written for calculating the number of other components in the charge, passing into it from the corresponding input material flows containing these components.

2) Total charge:

$$G_{ch}=\sum_i G_{ch}^{i} + G_{ch}^{ignt}$$

3) The composition of the charge, i.e. the content of individual components *(i)* is determined by the equation:

$$\alpha_{ch}^{i} = \frac{G_{ch}^{i}}{G_{ch}}$$

Melting process. Calculation of the amount and composition of the matte. The general equation for determining the mass amount of components in the charge is:

$$G_{ma}^{i}=\sum_{j=1}^{n} \beta_{j/ma}^{i}\, \alpha_j^i G j \approx \beta_{in.str/ma}^{i} \alpha_{in.str/ma}^{i} G_{ma} \quad (2)$$

where j - is the index of input material flows coming out of the charge preparation process. When calculating the amount of matte, all materials containing the sum of copper in all forms (oxidized, sulfide, etc.) For the conditions adopted in this problem, the input copper-bearing flow is the charge (index "ch"), the production charge (index "pch"), oxygen in the blast (index "oxyg"), air (index "air"), coal (index "coal"), converter slag (index "cslg"), clinker (index "cl").

Theoretically, depending on the form of copper in each material, the recovery factors from each input material to the output product will be different. Practically by analogy with the metallurgical calculation, we can consider them the same and use the average value of the copper extraction coefficient from the matte (the last term of equation 2).

1) The amount of copper (Cu) in the matte:

$$G_{ma}^{Cu}=\sum_{j=1}^{n} \beta_{j/ma}^{Cu}\, \alpha_j^{Cu} G_j=\beta_{ch/ma}^{Cu} \alpha_{ch}^{Cu} G_{ch} + \beta_{pch/ma}^{Cu} \alpha_{pch}^{Cu} G_{pch} + \beta_{cslg/ms}^{Cu} \alpha_{cslg}^{Cu} G_{cslg} + \beta_{cl/ma}^{Cu} \alpha_{cl}^{Cu} G_{cl}$$

Similarly, to equations, equations are written for calculating the number of other components in the matte passing into it from the corresponding input material flows containing these components.

In equations, the index *j* means input material flows containing the corresponding components (copper, sulfur, etc.)

4) Total amount of matte:

$$G_{ma} = \sum_i G_{ma}^{i} + G_{ma}^{ignm} = G_{ma}^{Cu} + G_{ma}^{Fe} + G_{ma}^{S} + G_{ma}^{Zn} + + G_{ma}^{Pb} + G_{ma}^{ignt}$$

5) Matte composition, i.e. the content of individual components *(i)*, is determined by the equation:

$$\alpha_{ma}^{i} = \frac{G_{ma}^{i}}{G_{ma}}$$

In metallurgical calculations, the composition of the matte is usually given by the content of copper and other components. In this case, the amount of matte is determined by the equation:

$$G_{ma} = G_{ma}^{Cu} \big/ \alpha_{ma}^{Cu},$$

where $\alpha_{шт}^{Cu}$ content of copper in the matte. The amount of any component (*i*) in the matte is determined by the expression:

$$G_{ma}^{i} = G_{ma} \alpha_{ma}^{i}.$$

Melt process. Calculation of the amount and composition of slag. Components from the feedstock and products of reactions occurring in the furnace pass into the slag: oxide reduction, oxidation, slag formation, etc.

The general expression for determining the number of components in the slag is obtained from the equation:

$$G_{sl}^{i} = \sum_j^n \beta_{j/sl}^{i} \alpha_j^i G_j \quad (3)$$

1) The amount of calcium oxide (CaO) in the slag

$$G_{sl}^{CaO} = \sum_j^n \beta_{j/sl}^{CaO}\, \alpha_j^{CaO} G_j = \beta_{ma/sl}^{CaO}\, \alpha_{ma}^{CaO} G_{ma} + + \beta_{pma/sl}^{CaO}\, \alpha_{pma}^{CaO} G_{pma} + \beta_{ksl/sl}^{CaO}\, \alpha_{ksl}^{CaO} G_{csl}$$

Similarly, to this equation, equations are written for calculating the amount and composition of slag of other components.

Calculation of the total amount of slag:

$$G_{sl} = G_{sl}^{CaO} + G_{sl}^{SiO_2} + G_{sl}^{Fe_2O_3} + G_{sl}^{MgO} + G_{sl}^{ignt}$$

Calculation of the quantity and composition of process off-gases. Exhaust technological gases are formed due to the blast supplied to the furnace: air (for combustion and transport of the pulverized coal mixture), oxygen, gas and gaseous products of chemical reactions of combustion, reduction, dissociation, evaporation of crystallization and ordinary moisture formed in the furnace, etc. [16].

Assuming that all input material flows are known and given the chemical reactions occurring in the furnace, it is possible to determine the mass amount of the main (accounted for) components and recalculate their content in the exhaust gases:

1) Gases from the reduction of charge oxides:

$$G^{CO} = \sum_j \beta_{j/sl}^{CO} \alpha_j^{CO} G_j$$

Thermal balance of the smelting process and the production of matte and slag in the Vanyukov furnace. The main sources of heat are (per *n* kg of charge):

1) Physical heat of the starting materials of the charge:

$$Q^{mat} = \sum_m^n M_m^{mat} \cdot C_m^{mat} \cdot T_m^{mat}$$

where Q^{mat} – heat materials;

M_m^{mat} – mass of *m*-th input material;

C_m^{mat} – the average heat capacity of the *m*-th input material;

T_m^{mat} –is the temperature of the *m*-th input (initial) material.

2) Heat of charge:

$$Q_{ch}^1 = \sum M_{ch}^{mat} \cdot C_{ch}^{mat} \cdot T_{ch}^{mat}$$

3) Converter slag heat:

$$Q_{csl}^2 = \sum M_{csl}^{mat} \cdot C_{csl}^{mat} \cdot T_{csl}^{mat}$$

4) Total physical heat of materials:

$$Q^{mat} = Q_{ch}^1 + Q_{csl}^2$$

5) Air blast heat:

$$Q_d^3 = \sum M_d^{air} \cdot C_d^{air} \cdot T_d^{air}$$

6) Heat of exothermic reactions

Exothermic reactions:

$$S + O_2 \rightarrow SO_2$$

$$CaO + SiO_2 \rightarrow Ca_2SiO_4$$

$$Fe_2O + SiO_2 \rightarrow Fe_2SiO_4$$

$$Q_{Ex} = -\sum dH_T \cdot \frac{M_{comp}}{M_m}$$

where Q_{Ex} - heat in melting;

$$Q_{Ex} = -(dH_T \cdot \frac{M_{S*O2}}{M_m} + dH_T \cdot \frac{M_L}{M_m} + dH_T \cdot \frac{M_B}{M_m})$$

where the designation L corresponds to Ca_2SiO_4, B - Fe_2SiO_4

7) Thermal energy due to fuel combustion (coal combustion):

$$Q_f = \sum q_f \cdot M_f$$

where q_f – the lower calorific value of fuel per working mass, kJ/kg

$$Q_f = \sum q_f \cdot M_f = q_{C_2H_8} \cdot M_{C_2H_8} + q_{C_4H_{10}} \cdot M_{C_4H_{10}}$$

where The main sources of heat consumption are (per *n* kg of charge):

The heat removed from the process products:

$$Q^{prod} = \sum_m^n M_m^{prod} \cdot C_m^{prod} \cdot T_m^{prod}$$

8) The heat of matte:

$$Q_{ma}^1 = \sum M_{ma}^{prod} \cdot C_{ma}^{prod} \cdot T_{ma}^{prod}$$

9) The heat of waste slag:

$$Q_{sl}^2 = \sum M_{sl}^{prod} \cdot C_{sl}^{prod} \cdot T_{sl}^{prod} + M_{sl}^{ign} \cdot C_{sl}^{ign} \cdot T_{sl}^{ign}$$

10) The heat of the dust:

$$Q_{dst}^3 = \sum M_{dst}^{prod} \cdot C_{dst}^{prod} \cdot T_{dst}^{prod} + M_{dst}^{ign} \cdot C_{dst}^{ign} \cdot T_{dst}^{ign}$$

11) The heat of gases:

$$Q_{gas}^4 = \sum M_{gas}^{prod} \cdot C_{gas}^{prod} \cdot T_{gas}^{prod}$$

12) Heat of endothermic processes

Endothermic reactions:

$$2CuFeS_2 \rightarrow Cu_2S + 2FeS + 0.5S_2$$

$$2Cu_5FeS_4 \rightarrow 5Cu_2S + 2FeS + 0.5S_2$$

$$FeS_2 \rightarrow FeS + 0.5S_2$$

$$Q_{endo} = -\sum dH_T \cdot \frac{M_{comp}}{M_m}$$

Thermal balance:

$$Q_{ma}^1 + Q_{ksl}^2 + Q_d^3 + Q_{Ex} + Q_f = Q_{th}^1 + Q_{sl}^2 + Q_{heat}^3 + Q_{gas}^4 + Q_{endo}$$

Development of a computer model for controlling the thermal and material regimes of the smelting process. A computer model for controlling the furnace modes is developed in MATLAB Simulink (see Figures 1-3). Figure 1 shows the general block diagram of the Vanyukov smelting process control model for thermal and material conditions.

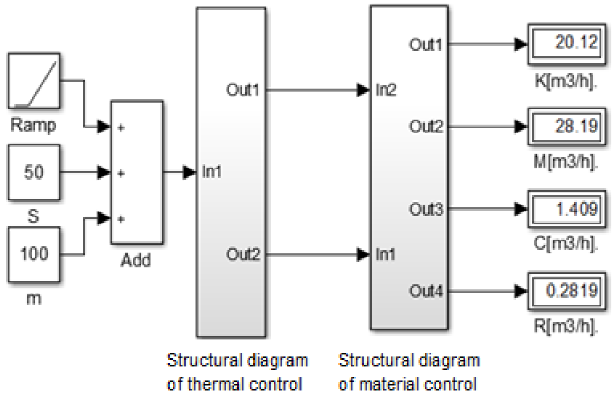

Figure 1 – Structural diagram of thermal and material control of the melting proces

As can be seen from Figure 1, the block diagram of the mathematical model consists of two subsystems: the heat balance calculation subsystem and the material balance calculation subsystem. The developed mathematical model for controlling the smelting process can quite well describe the dynamics of the state of the process, both when establishing influences aimed at increasing the heating of the furnace, and at reducing its heating.

Figures 2, 3 show: a subsystem for calculating the heat balance, which will allow, when calculating the material flows of the charge, to track changes in the thermal state of the melt (by the copper content in the matte) and the subsystems themselves for calculating the material flows of the charge. These subsystems for calculating the heat balance and material flows of the charge consist of blocks of mathematical operations and functional blocks of the Simulink Library.

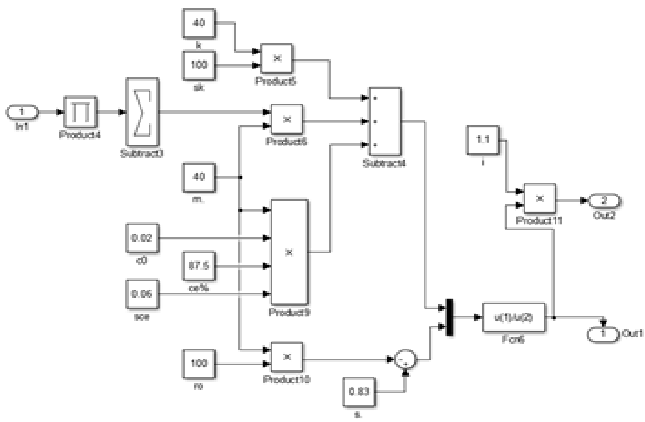

Figure 2 – Subsystem 1 for calculating the heat balance

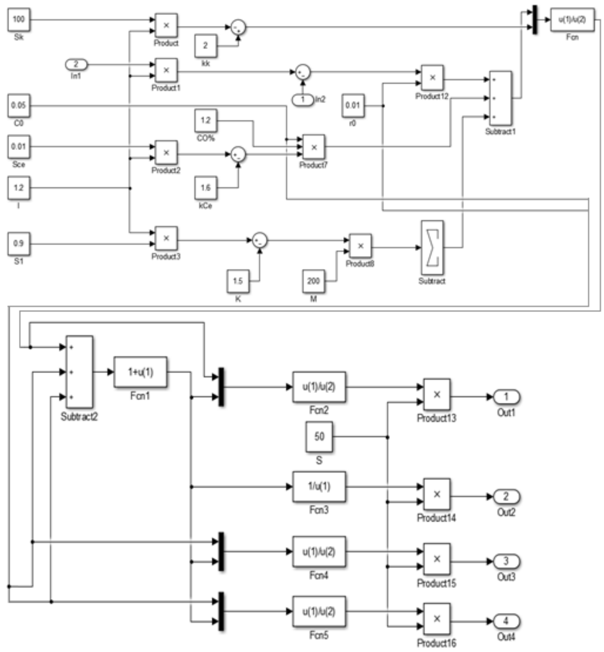

Figure 3 – Subsystem 2 for calculating the material flows of the charge

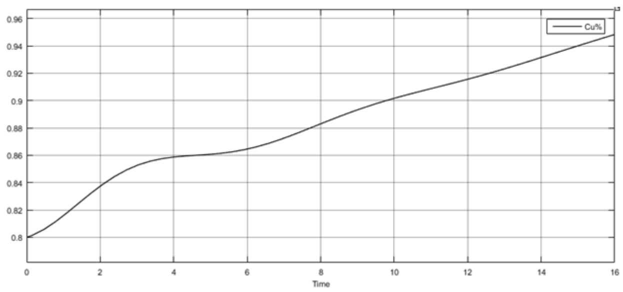

Figure 4 – Dynamics of changes in the copper content in the matte in the transition process

As can be seen from Figure 4, an oscillatory transient process in the furnace is observed if, after the disturbance is applied, it will have the opposite effect on the thermal state of the lower and upper stages of heat exchange. In this case, the overshoot value will be the greater, the more significant in magnitude and sign this difference is. The most predictable parameters affecting the copper content in the matte are changes in the matte load, blast moisture, and slag basicity.

The discussion of the results

The calculation of the dynamic characteristics of the furnace should be based on fundamental knowledge of the theory and practice of modern "autogenous" processes, as well as the general patterns of transient processes obtained using a dynamic model of the melting process [17].

The dynamic characteristics of the furnace through the various impact paths vary considerably depending on the properties of the molten raw material, and the design and operating parameters of the furnace. In this regard, it is advisable to determine the static parameters from the model, and the duration and magnitude of the delay of transient processes in the object should be related to the time of turnover of one volume of charge in the furnace [[18], [19]].

The change in the oxygen concentration in the blast and the flow of natural gas cannot be used as parameters for controlling the copper content in the matte. This is due to the variable influence of these parameters on the thermal regime of the melt. Forced regulation of natural gas flow and oxygen concentration in the blast to control the copper content in the matte can lead to results opposite to those expected [20].

Conclusion

The work carried out in this research showed the following results:

1) A mathematical model has been developed for the dependence of input and output material flows of the process of smelting copper concentrates in the Vanyukov furnace.

2) On the basis of equations of material and heat balance, the structure of a computer model has been developed for the purposes of operational planning and control of a complex technological process of melting.

3) On the basis of models it is possible to form the structure of a closed dynamic model (29-42), which takes into account both the kinetics and hydrodynamics of the processes flowing in the Vanuykov melting processes. However, creating an optimal control system is required to carry out work on identifying the model and verifying its adequacy, which requires the implementation of quite complex, lengthy, labor-intensive, and expensive studies, both the kinetics and hydrodynamics of the process.

2) Under the conditions described, it will be more efficient not to create a mathematical model of the complex process of the copper smelting process, but to develop a model for controlling this process based on the experience, knowledge, and intuition of operators-technologists working for a long time at this facility.

Conflict of interests

On behalf of all authors, the correspondent author declares that there is no conflict of interest.

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Материалдық және жылу режимін басқару мақсатында Ванюков балқытуының күрделі технологиялық кешені үшін математикалық модель әзірлеу

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ТҮЙІНДЕМЕ

Бұл мақалада Ванюков балқымасының (ВБ) күрделі технологиялық кешенін жедел жоспарлау және басқару мақсатында материал және жылу балансының теңдеулеріне негізделген кіріс және шығыс ағындарының тәуелділіктерінің статикалық теңдеулері түріндегі математикалық модель ұсынылған. Теңдеулердің негізінде MATLAB бағдарламалық пакетіндегі динамикалық бағдарламалау әдісіне негізделген компьютерлік модель жасалды. Төменнен үрлеумен әзірленген балқыту процесінің технологиясы негізінде жылу режимін басқару мақсатында өтпелі режимде үрлегенде оттегінің өзгеруі кезінде штейндегі мыс құрамының өзгеруінің динамикалық сипаттамалары зерттелді. Зерттеу нәтижесінде шихтаның материалды ағындарын есептеу кезінде балқыту процесін басқарудың әзірленген математикалық моделі балқытудың жылу күйіндегі өзгерістерді (штейндегі мыс мөлшері бойынша) бақылауға мүмкіндік береді. Бұл модель пешті қыздыруды арттыруға бағытталған әсерлерді орнату кезінде де, оның қызуын азайту кезінде де процестің күйінің динамикасын жақсы сипаттай алады. Ғылыми жаңалық алғаш рет балқыту өнімдерінің фурмалық және тұнба аймағында болатын процестерді сипаттайтын математикалық модель құрылымының жасалуында.

Түйін сөздер: технологиялық кешен, басқару жүйесі, статикалық модель, жылу режимі, мыс балқытуы

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Разработка математической модели для сложного технологического комплекса плавки Ванюкова с целью управления материальным и тепловым режимом

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АННОТАЦИЯ

В данной статье приводится математическая модель в ввиде статических уравнений зависимостей входных и выходных потоков на основе уравнений материального и теплового баланса для целей оперативного планирования и управления сложным технологическим комплексом плавки Ванюкова (ПВ). На основе уравнений, разработана компьютерная модель, основанная на методе динамического программирования в программном комплексе MATLAB. Исследованы динамические характеристики изменения содержания меди в штейне при изменении содержания кислорода в дутье в переходном режиме с целью управления тепловым режимом на основе технологии разработанного процесса плавки с продувкой снизу. В результате исследования, разработанная математическая модель управления процессом плавки при расчете материальных потоков шихты позволит отслеживать изменения теплового состояния плавки (по содержанию меди в штейне). Данная модель достаточно хорошо может описать динамику состояния процесса как при установлении воздействий, направленных на повышение нагрева печи, так и на снижение ее нагрева. Научная новизна заключается в том, что впервые разработана структура математической модели, описывающей процессы, протекающие в надфурменной зоне и зоне отстоя продуктов плавки.

Ключевые слова: технологический комплекс, система управления, статическая модель, тепловой режим, плавка меди

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