SYNTHESIS OF A CONTROL SYSTEM FOR THE TECHNOLOGICAL PROCESS OF BLENDING AND MELTING OF COPPER CONCENTRATES

Abstract. This paper describes the synthesis of a control system for the technological process of blending and melting of copper concentrates. A basic mathematical model of the process is constructed taking into account the kinetics of chemical reactions, that is, all equations represent a mathematical model that describes the main physico-chemical and thermal transformations occurring in the considered zones of the process of charging and electric melting of copper concentrates. In this work, it is assumed that physico-chemical transformations of matter take place in the main bath. Then the material balance of the main bath receiving zone consists of two items: the receipt of materials from zone III and the removal of materials with the resulting mat. Also, here the equations are a mathematical model describing the basic physico-chemical and thermal transformations occurring in the considered zones of the process of electric melting of copper concentrates. The constructed model can be further used in the field of automation of technological processes and productions, in metallurgy, in mechanical engineering, in industry.

Keywords. Copper concentrates, dynamics, physico-chemical processes, synthesis, blending, melting, technological process.

Introduction. The process of separating matte and slag is associated with the deposition of molten matte particles in the slag layer of the bath. The successful course of this process depends on the difference in the specific gravity of the materials, the viscosity of the slag, the temperature of the melt, etc. These factors largely determine the loss of valuable metals with slags. The loss of copper with waste slag is also influenced by the processes of dissolution and oxidation of sulfides.

The thermal energy required to carry out the process of ore-thermal electric melting is released in the slag bath (zone III) of the furnace as a result of its active resistance to electric current [1].

When constructing the mathematical model of zone III, the following assumptions were made that do not distort the overall picture of the process.
1. Settling matte particles are conventionally considered spherical.
2. The effect of the convective movement of slag on the settling of matte particles can be taken into account by introducing a correction factor in determining the flow of settling particles [2].

The system synthesis method is often used in the management and management of automated process control systems. And in this work we also use the synthesis method to control the technological process of mixing and melting copper concentrates.

To do this, we fully study the subject area, that is, the object of management. And for this technological process, we create a mathematical model. This topic is now very relevant in our country and abroad.
Materials and methods.

The settling rate of the matte particles is considered uniform over the entire height of the bath and is determined by the Equation 1:

$$
\nu_s = x \sqrt{\frac{4gd(\rho_M - \rho_s)}{3\rho_s \varepsilon}}.
$$

where $x$ is a correction factor that takes into account the effect of convective movement of slag on the deposition rate of matte particles;

$g$ is the acceleration of gravity (m/s$^2$);

$d$ is the diameter of the matte drop (m);

$\rho_M, \rho_s$ - according to the density of matte and slag (kg/m$^3$);

$\varepsilon$ is the coefficient of slag resistance to the movement of matte droplets, depends mainly on the viscosity of the slag in accordance with the empirical Equation 2 [3]:

$$
\varepsilon = \varepsilon_0 + K_{\varepsilon} \eta_s,
$$

where $\varepsilon$ and $K_{\varepsilon}$ are constant coefficients;

$\eta_s$ - the viscosity of the slag.

The dependence of the viscosity of the slag on the temperature and composition of the slag can be approximated by the Equation 3:

$$
\eta_s = \eta_0 - K_{\eta_s} G_{SiO_2} - K_{\eta_s} G_{FeO}.
$$

The drops of matte, when passing through the slag, dissolve in it in proportion to the surface of the drops.

Chemical losses of copper occur due to the course of an exchange reaction in the furnace bath Equation 4:

$$
Cu_2S + FeO = FeS + Cu_2O.
$$

The losses of sulfides with dump slags are proportional to the current number of matte particles in the slag. To account for the dissolution of sulfides from the surface of matte droplets into slag, we express the contact surface in terms of the weight of the sulfide particles Equation 5:

$$
S_c = \sigma N_c S_c = \sigma \frac{G_c}{\rho_c} S_c = \sigma \frac{4\pi r^2}{3} G_c = \sigma \frac{3}{\rho_c} G_c.
$$

where: $S_c$ - the total surface of all sulfide particles (m$^2$);

$N_c$ - the total number of sulfide particles;

$G_c$ - the total mass of all sulfide particles (kg);

$S_{ci}$ - surface of a single particle (m$^2$);

$\rho_c$ - average particle mass (kg);

$r$ - particle radius (m);

$\gamma$ - specific gravity of the particle (kg/m$^3$);

$\sigma$ is a coefficient that takes into account the non-sphericity of the Stein particles.

Then the amount of sulfide dissolved in the slag, taking into account the equation, can be represented as Equation 6:

$$
G_{cp} = K_c G_c
$$

where $K_c$ is the proportionality coefficient.

The oxidation of sulfides, which determines the chemical losses of valuable metals, occurs due to the reaction [4-6]. The reaction rate can be determined by the following expression Equation 7:
where:

$G_{Cu_2S}, G_{FeO}$ - weight quantities $Cu_2S$ and $FeO$ in the slag bath;

$K$ the conditional constant of the reaction rate, determined by the well-known Arrhenius law.

**Results.**

The flowchart of the technological process is shown in Figure-1.

![Flowchart of the technological process](image-url)
The current amount of oxidized copper by reaction (6), taking into account (7), can be written Equation 8:

\[
\frac{d\rho_{CuO}}{dt} = \frac{K_{CuO}}{\rho_{CuS}} \rho_{CuS} \rho_{FeO}.
\]  

(8)

The equation \( A_{FeS} = \{FeS, Cu_{2}S\} \) of the material balance for matte-forming and slag-forming substances \( B_{n} (n = CaO, SiO_2, FeO) \) in a slag bath, using the above equations to describe individual phenomena, will be written as Equations 9-12:

\[
\frac{d\rho_{III}^{A}}{dt} = \alpha_{Ae}^{II-III} G_{Ae}^{II} - K_{c} G_{c} - K_{s} G_{As} G_{Bn} - K_{me} G_{Ae}^{III} - \alpha_{Ae}^{III-Iv} G_{Ae}^{IV} H_{c},
\]

(9)

\[K_{c} = 0 \text{ if } l \neq FeS,\]

(10)

\[K_{s} = K_{Cu_{2}S}, i f \ l = Cu_{2}S,\]

(11)

\[
\frac{d\rho_{Bn}}{dt} = \alpha_{Bn}^{II-III} G_{Bn}^{II} - Y_{Bn}^{K} G_{Bn}^{K} + Y_{Bn} G_{s}^{b}.
\]

(12)

The amount of copper in the slag zone is determined by the Equation 13:

\[G_{Cu}^{III} = \beta_{1} G_{Cu_{2}S} + \beta_{2} G_{Cu_{2}O} + \beta_{3} G_{cp}^{III}.
\]

(13)

Then the loss of copper with waste slag will be recorded as Equation 14:

\[G_{Cu}^{III} = Y_{n} G_{Cu}^{III}.
\]

(14)

Where:

\( G_{Ae}^{II}, G_{Ae}^{III} \) - the amount of sulfide in zone II and III (kg);

\( \alpha_{Ae}^{II-III}, \alpha_{Ae}^{III-Iv} \) - coefficients taking into account the removal of sulfide from zone II to III and from zone III to IV;

\( K_{me} \) - a proportionality coefficient that takes into account the mechanical losses of sulfides with slags;

\( H_{c} \) - the height of the slag bath (m);

\( G_{Bn}^{K}, G_{Bn}^{III} \) - the amount of slag-forming substance in zones II and III (kg);

\( G_{Bn}^{K} \) - amount of converter slag to be poured (kg);

\( G_{me}^{me} \) - the amount of slag produced (kg);

\( \alpha_{Bn}^{II-III} \) - coefficient of removal of the slag-forming substance from zone II to zone II to zone III;

\( Y_{Bn}, Y_{Bn}^{K} \) - the content of the i-th slag-forming substance in the produced slag and converter slag;

\( \beta_{1}, \beta_{2}, \beta_{3} \) - coefficients determining the copper content in the relevant substances;

\( Y_{n} \) - the proportionality coefficient.

The following assumptions were made when compiling the equations of the thermal balance of zone III:

1. Electrical energy is converted into heat and distributed mainly in the slag layer.
2. The release of heat during the flow of current through the charge and matte is neglected due to its insignificance [7-8].
3. The amount of heat given to zone II is proportional to the temperature difference between the slag bath and the melting of the charge.
4. The slag resistance is proportional to the content of metal and silicon oxides in the slag, the temperature of the slag and can be represented by the following Equation 15:
Heat is spent on heat transfer to zone II, is lost due to heat transfer through the walls of the furnace into the environment and is carried away with the materials outside, and with the matte into the matte bath [9].

In general, the heat balance equation of zone III, which takes into account the main articles of heat arrival and consumption, has the Equation 16:

\[
\sum G_i G'_i \frac{dt}{dt} = Q_{st} + Q_s - Q_{3-2} - Q_s - Q_{st} - Q_{st}. \tag{16}
\]

The following notation is used in equation (17):

- \(Q_{st}\) - the amount of heat released when converting electrical energy into thermal energy Equation 17:

\[
Q_{st} = K_s \rho_s R_t^2. \tag{17}
\]

Where \(K_s\) is the coefficient that takes into account the transfer of energy to the melt;

- \(I\) – current (A);

- \(Q_{cs}\) - the amount of heat coming from the converter slag Equation 18:

\[
Q_{cs} = G_s^c C_s^c t_s^c. \tag{18}
\]

Where \(G_s^c\) is the amount of converter slag (kg);

- \(C_s^c\) - specific heat capacity of converter slag (kcal/kg.deg.);

- \(t_s^c\) - temperature of the converter slag (°C);

- \(Q_{3-2}\) – heat transferred to zone II Equation 19:

\[
Q_{3-2} = \alpha(t_s - t_m)w_0 C_sF_m. \tag{19}
\]

Where \(\alpha\) is the heat transfer coefficient;

- \(F_m\) - melting surface area of the charge (m²);

- \(w_0\) - conditional velocity of convective movement of slag;

- \(C_s\) - specific heat capacity of slag (kcal/kg.deg);

- \(Q_{3-4}\) – heat transferred to the matte bath Equation 20:

\[
Q_{3-4} = \alpha(t_s - t_{st})F_{st}. \tag{20}
\]

where \(F_{st}\) the surface of the matte bath (m²);

- \(Q_w\) - the amount of heat lost through the furnace wall Equation 21:

\[
Q_w = \lambda \frac{5x-2\lambda}{\sigma} F_w. \tag{21}
\]

\(\lambda\) - coefficient of thermal conductivity (kcal/deg.m.hour);

- \(F_w\) - the area of heat with the released slag;

- \(Q_{sl}\) - heat loss with the released slag Equation 22:

\[
Q_s = G_s^c C_s t_{sl}. \tag{22}
\]

Where is \(Q_{sl}\) – heat transferred to the matte zone as a result of settling of matte particles Equation 23:
where is $C_e$ the heat capacity; $l$-th sulfide (kcal/kg deg.).

A block diagram of the algorithm for calculating additional electrical variables is shown in Figure 2.

\[ Q_{st} = \sum_l \alpha_l^3 \gamma l \beta K_{stl} C_e t_{stl}. \]  \hspace{1cm} (23)

Figure 2 - Block diagram of the algorithm for calculating additional electrical variables

Taking into account the expressions, we obtain the equation of the thermal balance of zone III in the following Equation 24:

\[ C_e^p G_{st} \frac{dt_{sl}}{dT} = K_s \rho s I^2 + G_w^K C_{stl} t_{sl} - \alpha (t_{sl} - t_m) w_0 C_{stl} F_m - \alpha (t_{sl} - \text{)} t_{st}, \]

\[ F_{st} = \text{\frac{A \left(t_{sl} - t_{w} \right)}{\sigma}} F_w - G_w C_{stl} t_{sl} - \sum_l \alpha_l^3 \gamma l \beta K_{stl} G_{stl}^2 \]  \hspace{1cm} (24)

In this case, the equation of the material balance of zone IV will be written Equation 25:

\[ \frac{d \alpha_l A_l}{dT} = \text{\frac{A_{l1} l - \alpha l \gamma l}{H_{stl}}} v_k - \beta A_l C_e^2, \]  \hspace{1cm} (25)

where is $\beta_{A_l}$ the proportion of l-th sulfide in the produced matte [10].

Discussion.
The main stages of the arrival and consumption of heat in the formulation of the heat balance equation of zone IV are:
a) the arrival of heat at a temperature from zone III with settling matte particles;
b) heat input due to heat transfer from zone III;
c) heat loss with the released matte and the environment through the walls and the hearth

Equation 26:

\[
(\sum_{i} C_{A_l} G_{A_l}) \frac{dt_{st}}{dt} = (\sum_{e} r_{e} G_{st} C_{e}) t_{st} + \alpha (t_{st} - t_{st}) F_{st} - \frac{\lambda (t_{st} - t_{w})}{\sigma} h_{st} S_{n} - \frac{\lambda'}{\sigma} (t_{st} - t_{n}) F_{n},
\]

Where is \( t_{st} \) the temperature in the matte bath (\(^{0}\)C);
\( \lambda, \lambda' \) – respectively, the thermal conductivity of the walls and the hearth of the furnace (kcal/ deg.m.hour);
\( t_{w}, t_{n} \) – accordingly, the temperature of the wall and the spring (\(^{0}\)C);
\( \sigma, \sigma' \) – accordingly, the thickness of the walls and the hearth (m);
\( S_{n} \) – the perimeter of the furnace (m);
\( F_{n} \) – the area of the hearth (m\(^2\)).

The model we have built can be further applied in various fields of automated process control systems and production, in metallurgy, in energy, in mechanical engineering, in industry.

Conclusion.

The constructed basic mathematical model of the process, taking into account the kinetics of chemical reactions, that is, the synthesis of a control system for the technological process of charging and melting of copper concentrates, represents all equations, expressions, that is, a constructed mathematical model that describes the basic physico-chemical and thermal transformations occurring in the considered zones of the process of charging and electric melting of copper concentrates.

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МЫС КОНЦЕНТРАТТАРЫН ШИХТІЛЕУ ЖӘНЕ БАЛҚЫТУДЫҢ ТЕХНОЛОГИЯЛЫҚ ПРОЦЕСІН БАСҚАРУ ЖҰЙЕСІНІҢ СИНТЕЗІ

Аңдатпа.  Бұл жұмыста мыс концентраттарын шихтілеу мен балқытудың технологиялық процесіндегі басқару жұйесін синтезі сипатталған. Химиялық реакциялардың кинетикасының оқырымдары, процессін негізі математикалық моделі құрылды, яғни барлық теңдеулер мыс концентраттарын шихтілеу және электрмен балқыту процесінің қарастырылған аймақтарында болатын негізгі физика-химиялық ене жылу түрлікдірулерін сипаттайтын математикалық модельді білдіреді. Бұл жұмыста заттың физика-химиялық түрленуі негізінен нәрселер және материалдардың сыртқы күндірт көздері орналасқан (IV аймақ) екі баптан тұрады: Құрылған модельдің математикалық ортақтығын ең айман материалдардың түсіуі және алынған төменішпен материалдарды алып тастау. Сондай-ақ, мұнда тәндеулер мыс концентраттарын электрмен балқыту процесінің қарастырылған аймақтарында болатын негізгі физика-химиялық және териологиялық түрлікдірулерді сипаттайтын математикалық модель болып табылады. Құрылған модель
болашақта технолгиялық процестер мен ондірістерді автоматтандыру саласында, металлургияда, машина жасауда, өнеркәсіпте қолдана алады.

Түйінді сөздер. Мыс концентраттары, динамика, физика-химиялық процестер, синтез, шихтілеу, балқыту, технологиялық процесс.

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СИНТЕЗ СИСТЕМЫ УПРАВЛЕНИЯ ТЕХНОЛОГИЧЕСКИМ ПРОЦЕССОМ ШИХТОВКИ И ПЛАВЛЕНИЯ МЕДНЫХ КОНЦЕНТРАТОВ

Аннотация. В данной работе описывается синтез системы управления технологическим процессом шихтовки и плавления медных концентратов. Построена базовая математическая модель процесса с учетом кинетики химических реакций, то есть все уравнения представляют математическую модель, которая описывает основные физико-химические и тепловые превращения, происходящие в рассматриваемых зонах процесса шихтовки и электроплавления медных концентратов. В этой работе предполагается, что физико-химические превращения вещества происходят в основной ванне. Тогда материальный баланс зоны приема матовой ванны (зона IV) состоит из двух статей: поступления материалов из зоны III и удаления материалов с полученным матом. Также здесь уравнения представляют собой математическую модель, описывающую основные физико-химические и термические превращения, происходящие в рассматриваемых зонах процесса электроплавки медных концентратов. Построенная модель в дальнейшем может быть использована в области автоматизации технологических процессов и производств, в металлургии, в машиностроении, в промышленности.

Ключевые слова. Медные концентраты, динамика, физико-химические процессы, синтез, шихтовка, плавление, технологический процесс.

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