Development of a control subsystem to stabilize burden materials charging into a furnace

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Abstract. An approach to the development of a control subsystem for the technological process of smelting copper-Nickel raw materials, which allows to stabilize the loading of charge materials into the furnace, is proposed. The structure of the control subsystem is described. The control problem, the control quality criterion, the control object model, control and perturbing effects are considered. Single-circuit and combined variants of subsystems of quality management of products of melting are offered. It is established that the control subsystem stabilizing loading of charge materials in the Vanyukov furnace should be combined: in addition to the feedback loop, it should contain a perturbation compensator on one channel, but as calculations show, the quality improves if all perturbations are compensated.

1. Introduction

The technological process of smelting copper-nickel sulfide raw materials in the melt sheet (in a liquid bath), named in honor of its author V.N. Vanukov as the Vanukov process (VP), is today one of the promising technique of processing of copper and copper-nickel sulfide materials. The VP complex consists of a burden-charging subsystem, a blast supply subsystem, a subsystem for the tapping of matte and slag, a subsystem for waste gases removal, and the furnace itself.

Control over the VP complex can be arranged in two ways. The first one is to keep stable all the supply streams and material flows in the order of the nominal value. The second is to control the process by feedback of the ratio of charging the burden and the oxygen delivery flow (blast rate with known oxygen content). Thus, for both methods, it can be concluded that it is necessary to stabilize the charge link.

Control over the VP complex is as follows. First, it is necessary to stabilize all the supply streams and material flows within the prescribed limits. Secondly, when charging, the task is to maintain the ratio of the volumes of the burden charged and the oxygen flow supplied. The control over the process of stabilization of the ratio of burden charge and oxygen flow is achieved by maintaining the charge within the prescribed limits and controlling the blast flow.

The research is relevant due to the necessity to improve the quality of the smelting products of copper-nickel sulfide raw materials in the Vanukov furnace by stabilizing the furnace charging parameters with the required accuracy, which will minimize the influence of the “human factor.”

The objective of the work is to improve the quality of the smelting process control of copper-nickel sulfide raw materials in the Vanukov furnace.

2. Description of the smelting technology for copper-nickel sulfide raw materials in the Vanukov
furnace

The metallurgy of copper refers to the most energy-consuming and unsustainable industries. The production of copper is accompanied by emissions of sulfur-containing gases, toxic metal oxides, nitrogen oxides, and greenhouse gases into the atmosphere as well as the contamination of soil and groundwater. Processing of copper sulfide raw materials is a rather difficult task since copper ores are raw materials of a relatively poor composition.

Due to that the Vanukov process in the metallurgy of copper has been well established in terms of both technology and hardware, it allows high productivity processing of raw materials and has a wide range of capabilities for controlling the technological mode of smelting.

The processed burden (ore, concentrate) without preliminary preparation (fine grinding, deep drying, etc.) is conveyed to the furnace through the charging device. Once on the surface of the bath, the burden moves deep into the melt, vigorously mixes with it, and smelts under high temperatures. Depending on the composition of the raw materials, either air or technical oxygen is used as an oxidant in the furnace. The air blasting is fed into the melt through special tuyeres located on both sides of the bath in the side walls of the furnace. Liquid products of melting are divided into matte (melt of sulfides) and slag (melt of oxides), which, when accumulated, are removed from the unit through the end wall sides of the furnace.

The physicochemical process consists in the decomposition of higher sulfides into sulfides. See the main reactions describing the smelting process of copper-nickel sulfide raw materials below:

\[
\begin{align*}
2 \text{CuFeS}_2 & = \text{Cu}_2\text{S} + 2 \text{FeS} + \frac{1}{2} \text{S}_2 \\
2 \text{CuFeS}_3 & = \text{Cu}_2\text{S} + 4 \text{FeS} + \frac{1}{2} \text{S}_2 \\
3 \text{NiFeS}_2 & = \text{Ni}_3\text{S}_2 + 3 \text{FeS} + \frac{1}{2} \text{S}_2 \\
\text{Cu}_2\text{S} + \frac{3}{2} \text{O}_2 & = \text{Cu}_2\text{O} + \text{SO}_2 \\
\text{Ni}_3\text{S}_2 + \frac{7}{2} \text{O}_2 & = 3 \text{NiO}_2 + 2 \text{SO}_2 \\
\frac{1}{2} \text{S}_2 + \text{O}_2 & = \text{SO}_2
\end{align*}
\]

The main parameters for controlling the smelting process are as follows: the total burden smelted, the total blast rate, technical oxygen flow, and the oxygen content in the oxyhydrogen mixture. These variables de facto completely control the Vanukov process and determine the copper content in matte.

3. Description of the control subsystem stabilizing the charging of burden materials into the furnace

Stabilization of the burden charging by quantity and quality is achieved by measured and not measured disturbance suppression. To determine the structure of the VP complex automatic control system, which reaches the extremum of the selected quality criterion, the frequency decomposition shall be performed based on the hierarchical control over the technological modes.

For the Vanukov process, the subsystem for the burden preparation control can be represented in Fig. 1.

High-frequency subsystems (HFS) form belt feeders (local input regulator), stabilizing the flows of the certain components of the burden $Q_i$, charged into the furnace (conditionally, all these flows are shown by arrows outside the rectangle of the control object (CO)). These subsystems suppress high-
frequency disturbances – variations in the characteristics of devices that provide transportation of raw materials and supplies.

![Diagram](image)

**Figure 1.** The subsystem for the burden preparation control

The mid-frequency subsystems (MFS) suppress the actions of those components of the disturbances \( V_i \) and \( A_{jk} \), which cause medium-frequency variations of the \( G_c \) and \( R_{in} \) output of the product \( G \) and indices \( R_i = \{ A_i, \vartheta_{ui} \} \) (\( A_i \) – interim products composition indices, \( \vartheta_{ui} \) – technological mode parameters). To stabilize these indices, mid-frequency systems change the values of \( Q_{ku} \) – nominal of flows assigned as tasks to the subsystems of the VP. The tasks of the mid-frequency subsystems are the operationally planned output of the \( W_c \) products and the regulatory values \( R_{in} \) of the \( R_i \) parameters.

Thus, for practice, a division of the control task into agreed subtasks is achieved reasonably well; these subtasks are solved by different subsystems controlling the technological complex operating in different frequency ranges.

The practical application of the described above methods of evaluation of the disturbance suppression reasonability will be considered on the example of the synthesis of a control subsystem stabilizing the concentration ratio of \( Cu \) and \( SiO_2 \) in the burden \( B = \frac{Cu}{SiO_2} \) prepared by mixing two types of raw materials (copper concentrate and flux) in the process line of the CO (Fig. 1). The main uncontrollable disturbances that cause undesirable changes in the \( \beta \) ratio of \( B \) are variations \( \alpha_1 \) and \( \alpha_2 \) of the content of the components \( A_1 (Cu) \) and \( A_2 (SiO_2) \) in the in the substances to be mixed. Controlling action is the change in dosage (ratio of flows \( Q_1 \) and \( Q_2 \)) of the mixing substances \( \mu \).

The diagram of Fig. 1 represents two belt feeders (they are marked conditionally with rectangles \( F_1 \) and \( F_2 \)). The capacity of the feeder \( F_1 \) is set so that the required flow \( Q \) of the burden is provided. There are weight measuring elements \( MF_1 \) and \( MF_2 \) acting as the measures of the flows \( Q_1 \) and \( Q_2 \). Based on the results of measuring the flows of the mixing materials, the high-frequency subsystem forms such changes in the feeder \( F_2 \) so that to ensure the required mixing ratio of the mixing materials.

For MFS, the mid-frequency subsystem stabilizing the ratio \( B \) (the dashed lines in Fig. 1), the changes \( \mu \) will be the controlling actions. Two options of technological control are suitable for their formation.
The first option is the cheapest and easiest to operate: the \( \mu \) controls are only formed based on the results of measuring the deviations \( \beta \) of the controlled ratio \( B \) from the set value \( B_H \). Then the MFS subsystem will have only one feedback loop, which operates on the PI-algorithm, for example.

The second option is to measure not only the value of \( \beta \) but also the disturbances – the \( \alpha_1 \) and \( \alpha_2 \) deviations of the values \( A_1 \) and \( A_2 \) from their nominal (average) values of \( A_{1H} \) and \( A_{2H} \). Then the MFS subsystem will include not only a feedback loop but also a disturbance compensator. This option is more expensive than the first one, mainly because of the larger number of measurements.

In this regard, the synthesis of the MFS subsystem will be carried out according to the following plan:
1. Formulate precisely the control task (designate a performance criterion of control, describe constraints and disturbances);
2. Synthesize the simplest and cheapest first option of the system and determine whether it meets the control objectives;
3. If the synthesis of the first option of the system does not meet the quality control, synthesize the second option.

### 4. Formulation of the control task

There are the least favorable conditions of technological control, which are very frequent for metallurgical enterprises, when the values of \( \beta, \alpha_1 \) and \( \alpha_2 \) can be measured only by analyzing discretely sampled mixtures and mixing substances. Then it is reasonable to formulate the control task in the form of minimizing the costs of creating and operating the MFS subsystem, which ensures the stabilization of the quantity \( B \) with such accuracy that the variance \( D_{\beta} \) of the variations \( \beta(t) \) does not exceed the value \( D_{\beta \max} \).

With a precision sufficient for calculations, at the stage of development of the control system, the variance \( D_{\beta} \) of the controlled value \( \beta(t) \), characterizing the error of the system can be estimated as:

\[
D_{\beta} = 2 \cdot \int_{0}^{\infty} S_\beta(\omega) d\omega = 2 \cdot \int_{0}^{\infty} S_x(\omega) \left| \frac{1}{1 + F_x(j\omega) \cdot \Phi(\omega)} \right|^2 d\omega , \tag{1}
\]

where \( S_\beta(\omega) \) – spectral density of the controlled quantity \( \beta(t) \), \( F_x(j\omega) \) – transfer function of the linear process model, \( \Phi(\omega) \) – transfer function of perturbation compensator.

The transfer functions of the CO linear model are presented in the form of:

\[
F_x(j\omega) = \frac{K_x}{1 + j\omega T_x} e^{-j\omega \tau_x}, \quad x = \alpha_1, \alpha_2, \mu \tag{2}
\]

The spectral density functions \( S_{\alpha_1}(\omega) \) and \( S_{\alpha_2}(\omega) \) of stationary random disturbances \( \alpha_1(t) \) and \( \alpha_2(t) \) are described by formulas:

\[
S_x(\omega) = \frac{D_x \cdot \lambda_x}{\pi \cdot \left( \lambda_x^2 + \omega^2 \right)}, \quad x = \alpha_1, \alpha_2 \tag{3}
\]

If \( D_{\beta \max} = 0.5 \) then it is assumed that the measurement period \( T_\tau \) and the delay in obtaining its results \( \tau_\mu \) are the same for determining the values \( \beta, \alpha_1 \) and \( \alpha_2 \), and by the standard and technological capabilities of the analytical control service \( T_\tau = 4 \text{ h} \) and \( \tau_\mu = 0.5 \text{ h} \).
The description of the equality type constraints in the form of a linear model and the study of perturbation properties on the basis of production data and previous studies are summarized in Table 1.

**Table 1. The description of a linear model CO and disturbances**

| Designation of the signal \( x \) at the input of the CO | The parameters of the transfer function \( F_x(j\omega) \) | The parameters of the spectral density \( S_x(\omega) \) |
|---------------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| \( K_x \)                                              | \( T_x, \ h \)                                 | \( \tau_x, \ h \)                                 |
| \( D_x \)                                              | \( \lambda_x, \ h^{-1} \)                      |
| \( \alpha_1 \)                                         | 0.013                                          | 4.90                                            | 0.038                               | 2543.82                        | 0.0773                        |
| \( \alpha_2 \)                                         | -0.051                                         | 5.75                                            | 0.038                               | 3645.17                        | 0.0096                        |
| \( \mu \)                                              | 0.333                                          | 5.26                                            | 0.003                               | -                               | -                              |

Substituting the original data (Table 1) to formulas (2) and (3) get the transfer functions of the control object:

\[
F_{a_1}(j\omega) = \frac{0.013}{1+4.90j\omega} \cdot e^{-0.038j\omega},
F_{a_2}(j\omega) = \frac{-0.051}{1+5.75j\omega} \cdot e^{-0.003j\omega},
F_{\mu}(j\omega) = \frac{0.333}{1+5.26j\omega} \cdot e^{-0.003j\omega} - \text{and spectral density functions: } S_{a_1}(\omega) = \frac{2543.82 \cdot 0.0773}{\pi \cdot (0.0773^2 + \omega^2)},
S_{a_2}(\omega) = \frac{3645.17 \cdot 0.0096}{\pi \cdot (0.0096^2 + \omega^2)}
\]

5. **A single-loop option of the MFS subsystem**

The feedback loop uses the results of discrete delayed control (DC).

Discrete delay control of quantities \( \beta(t) \) prevents analog description of feedback loops in APCS of metallurgical industry, so in practice for the application of the ratio (1) is necessary in the transfer control function \( F_{\mu}(j\omega) \) to replace the delay of the control object \( \tau_{\mu} \) with a dummy value \( \tau'_{\mu} \):

\[
\tau'_{\mu} = \tau_{\mu} + 0.5 \cdot T_{\beta} + \tau_{I\beta}
\]

where \( T_{\beta} \) – period measurement the value of \( \beta \), \( \tau_{I\beta} \) – delay of results of discrete measurements of \( \beta \).

\( \tau'_{\mu} = 0.003 + 0.5 \cdot 4 + 0.5 = 2.503 \ h \)

The optimal values of the parameters \( K_p \) and \( \theta \) of the transfer function

\[
\Phi_{\beta}(j\omega) = K_p \cdot \left(1 + \frac{1}{j\omega\theta}\right),
\]

simulating a discrete analogue of the PI-algorithm are determined by formulas:
\[
K_\mu = \frac{0.7 \cdot T_\mu}{K_\mu \cdot \tau'_\mu}, \\
\theta = 0.7 \cdot T_\mu \tag{6}
\]

So that, we get:
\[
K_\mu = \frac{0.7 \cdot 5.26}{0.333 \cdot 2.503} = 1.42, \\
\theta = 0.7 \cdot 5.26 = 3.682
\]

Substituting the calculated data in (5) find the transfer function of the PI-regulator
\[
\Phi_\beta (j\omega) = 1.42 \left( 1 + \frac{1}{3.682j\omega} \right)
\]

Taking into account the non-correlated oscillations of \(\alpha_1\) and \(\alpha_2\) of the contents of components \(A_1\) and \(A_2\) in different substances, it can be assumed that
\[
D_\beta = 2 \int_0^\infty \left( S_{\alpha_1}(\omega) \cdot |F_{\alpha_1}(j\omega)|^2 + S_{\alpha_2}(\omega) \cdot |F_{\alpha_2}(j\omega)|^2 \right) \frac{1}{1 + F_{\beta}(j\omega) \cdot \Phi_\beta(j\omega)}^2 \, d\omega \tag{7}
\]

After numerical integration using the data obtained above, we obtain:
\[
D_\beta = 2.631
\]

Comparing the obtained variance value of oscillations \(D_\beta\) with the adopted above limitation \(D_{\beta_{\text{max}}} = 0.5\) come to the conclusion that the single-loop option of a subsystem for furnace charging stabilization is not sufficient to ensure the required quality of process control.

6. A combined version of the MFS subsystem

It may turn out that to fulfill the condition
\[
D_\beta \leq D_{\beta_{\text{max}}} \tag{8}
\]

it will be enough to compensate not both disturbances, but only one of them. Therefore, we calculate three variance values \(D_{\beta'}\).

\(D_{\beta'}\) - in the case when the disturbance \(\alpha_1\) is compensated, the disturbance \(\alpha_2\) isn’t measured;

\(D_{\beta''}\) - in the case when the disturbance \(\alpha_2\) is compensated, the disturbance \(\alpha_1\) isn’t measured;

\(D_{\beta'''}\) - in the case when both disturbances are compensated

Given the non-correlated disturbances, we obtain:
\[
D_{\beta'} = 2 \int_0^\infty \left( 2 \cdot S_{\alpha_1}(\omega) \cdot |F_{\alpha_1}(j\omega)|^2 + S_{\alpha_2}(\omega) \cdot |F_{\alpha_2}(j\omega)|^2 \right) \frac{1}{1 + F_{\beta}(j\omega) \cdot \Phi_\beta(j\omega)}^2 \times \\
\times \left[ 1 - \frac{\sin(T_1 + \tau_1) \cdot \omega - \sin \tau_1 \cdot \omega}{T_1 \cdot \omega} \right] \, d\omega \tag{9}
\]
Substituting the available data in the formulas (9), (10), (11) we get:

\[ D'_\beta = 0.277, \quad D''_\beta = 0.189, \quad D'''_\beta = 0.127. \]

Comparing the obtained variance value of oscillations \( D_\beta \) with the adopted above limitation \( D_{\beta\text{max}} = 0.5 \) come to the conclusion that all dispersion values \( D_\beta \) obey the ratio (8). Thus, to minimize costs for establishment and operation of the MFS subsystem providing stabilization of the value \( B \) with such an accuracy that dispersion \( D_\beta \) of the disturbances \( \beta(t) \) does not exceed the values \( D_{\beta\text{max}} \) the operator shall limit the disturbance suppression \( \alpha_1 \) only, while it is not reasonable to measure the disturbance \( \alpha_2 \).

Thus, the MFS subsystem must be a combined system: except the feedback loop, it must contain the disturbance compensator \( \alpha_1 \).

7. Conclusions

1. Quality improvement of the target smelting products (matte and slag) is possible by stabilizing and sufficiently rigid linking of input mass flows and blasting modes due to the introduction of the proposed control subsystem, which will minimize the influence of the “human factor” by stabilizing the charge of burden materials in the Vanukov furnace with disturbance suppression.

2. The performed calculations provide a wide range of capabilities for a technical solution to suppress disturbing effects and their implementation in practice.

Thus, the control subsystem stabilizing the charging of burden materials in the Vanukov furnace must be a combined system: in addition to the feedback loop, at least it must contain a disturbance compensator on one channel, but the calculations show that the quality is improved if all disturbances are suppressed.

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