Implementation of fuzzy logic in the smelting process of control algorithms of copper-nickel sulfide materials

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Abstract. The analysis of control quality of technological process of melting of copper-Nickel sulfide materials is carried out. The structure of the automatic melting control system is proposed, information and control channels are described. The algorithm of process control using fuzzy logic, which allows stabilizing the copper content in the matte within the specified limits.

1. Introduction

It is quite difficult to imagine the functioning of any technological facility without an automated control system today. In a market competitive environment, enterprises are forced not only to ensure the safety and sustainability of technological processes, but also to constantly improve their economic efficiency. Certainly, the most obvious method of improving the efficiency of technological processes is the improvement of technological schemes, hardware design of a technology and modes of technological processes. However, under this approach, only a part of the savings reserves can be benefited. The most significant effect can be obtained by improving automated process control systems by integrating the intellectual component of the mathematical apparatus that operates on the basis of fuzzy logic algorithms, neural networks, etc. into the control system [1-3]. To obtain a flowchart of the process control algorithm, it is necessary to carry out a full analysis of a technological process, determine the place of the mathematical apparatus in the structure of the process control system and set limitations imposed on the basic parameters of the process.

2. Controlled object analysis in the system

The solution of the problem in question is observed on the example of processing the operational control data set of the actual process of smelting copper-nickel sulfide raw materials in the Vanukov furnace (Vanukov process).

The Vanukov process in copper metallurgy is used-on both in terms technology and hardware [4, 14] allowing processing raw materials with high productivity and has wide possibilities in terms of control of the technological mode of smelting.

The processed furnace charge (ore, concentrate) is fed into the furnace from the top using the charging device without any preliminary preparation (fine grinding, deep drying, etc.). Once on the surface of the bath, the furnace charge is moved deeper into the smelt, vigorously mixed with it and is smelted under the influence of high temperatures. There is an oxygen-air mixture (OAM) used as an oxidizer in the furnace, depending on the composition of the raw material. The blast (OAM) is fed into the smelt through special tuyeres located on both sides of the bath in the side walls of the furnace. Liquid
Smelting products are divided into matte (sulphide smelt) and slag (oxide smelt), which, as they accumulate, are removed from the unit from the end sides of the furnace.

The main parameters for controlling the smelting process are the following: the total consumption of the furnace charge, the total consumption of the blast (oxygen-air mixture – OAM), the consumption of technical oxygen and the oxygen content in the OAM. These variables virtually completely control the Vanukov process and determine the copper content in the matte.

Smelting control is currently carried out by technical personnel based on their own experience and a subjective analysis of the indications of instrumentation, data obtained from visual observations, results of chemical analyzes received with delay and other information the personnel have on the state of individual components of the technological process, as well as on the basis of preliminary calculations of material and heat balances [5,6].

The purpose of the smelting process control of copper-nickel sulphide raw materials is to obtain a matte of a given composition, since the quality of the matte (copper content in the matte) received for further conversion affects the technical and economic indicators of the further stages of copper production: blast consumption, purge duration, the amount fluxes used and the resulting converter slag, thermal mode of the process, etc.

The composition of the matte in terms of copper content therein is regulated by changing the ratio of the oxygen in the blast and the amount of the furnace charge with a constant flow rate of natural gas.

The analysis of the operational control data of the Vanukov process for 2016 and 2018 showed (Figure 1) that the copper content in matte (C\textsubscript{Cu}) varies from 50 to 68%. Therefore, there is a need to stabilize the copper content in the matte.

The state of the furnace is constantly changing, so when controlling the process, it is necessary to avoid imbalances inside the furnace between the charged materials and the pressure of the exhaust gases. Matte quality improvement (stabilization of the copper content in the matte within the specified limits) is possible by fairly tight coupling of the mass fluxes charged and blast modes by introducing an automated control system that includes a quantification model of the copper content in the matte in the control loop allowing reducing the influence of “human factor” to a minimum. In this regard, there was an automatic control system developed using fuzzy logic algorithms. The implementation of fuzzy logic algorithms involves the use of a computer control similar to that performed by a qualified operator by presenting his work methods with the use of control rules as a model [7-9]. The control rules relate the assessment of the controlled object state with the sequence of operations using the statements “IF ... THEN”, divide the space of input variables into areas and indicate the sequence of operations in each local area [12, 13].

![Figure 1. Histogram of the distribution of the copper content in the matte: a) dates of 2016 year, b) dates of 2018 year](Image)
3. Block diagram of the control system

To improve the quality of the smelting process control [10,11], a block diagram has been developed for an automated system for controlling the copper content in matte, shown in Fig. 2, which includes the Vanukov furnace 1, equipped with charge funnels 2. There are tanks 3 installed in the Vanukov furnace charge system to feed bulk materials (copper concentrate, ore, flux, coal and recycled materials). Under the tanks 3 there are belt feeders 4 installed to dose charge materials loaded into the furnace. Charge materials are fed from the feeders 4 to the assembly conveyors 5, with the help of which they are fed through the charge funnels 2 into the reaction zone of the Vanukov furnace.

![Block diagram of the control system](image)

**Figure 2.** Block diagram of the control system.

Measuring channels 10-18 are designed to receive information about the instantaneous values of the relevant parameters (flow rate and loading rate of charge materials and blast flow rate) and have direct access to the information collection and preprocessing block 6. The information collection and preprocessing block 6 is connected to the switching unit 7, either activating the automatic process control mode using the control unit 8 according to the algorithm or deactivating it, and transfers all the information to the automated workplace (AWP) 9 of the operator. The control unit 8 according to the algorithm is connected with devices 19 for generating a control action on the flow rate of technical oxygen, 20 and 21 for generating a control action on the flow rate and loading speed of charge materials. Using the AWP 9 the operator also has the ability to influence the flow rate and loading rate of charge materials and technical oxygen through direct manual control of control output devices through the direct task setups 22 for technical oxygen consumption, 23 and 24 flow rate and load rate of charge materials.

Information on the values of the measured current smelting parameters is transferred to the information collection and preprocessing block 6 through the information transfer channels 10-18 in order to calculate the main parameter (total consumption of charge materials \( G_s \), t/h) and assigning the process to one of the established areas \( \{ G_{-1}, G_0, G_{+1} \} \) (Figure. 3).

In addition, the ratio of the flow rate of technical oxygen to blast per ton of charge materials \( \frac{m_3}{t \text{ of charge}} \) is additionally determined, and in case of the change gradient over 10% of the prescribed value, the total consumption of charge materials and technical oxygen is adjusted depending on the fact in which area the main parameter is, until reaching the \( G_0 \) area.
$G_{-1}$ area (Figure 3) is characterized by insufficient consumption of technical oxygen per ton of charge materials for the oxidation of sulfides to proceed. In this regard, oxidation reactions do not proceed in full and the matte is obtained with a low copper content. In this case, the control in the automatic mode is stopped, the manual control mode is activated, and the process is carried out with an increase in the consumption of charge materials and the consumption of technical oxygen blast per ton of charge materials ($m^3/t$ of charge) until reaching the $G_0$ area.

The $G_0$ area is characterized by the highest stability of all process parameters: hydrodynamic, energy, and physicochemical ones. In this case, the smelt is maintained in the initial state, the process proceeds without sharp spikes and local extrema which indicates the smoothness of the flow of all physicochemical reactions. Thus, the $G_0$ area (Fig. 3) is effective for obtaining matte with a high copper content and stable composition and it should be sought during the smelting process. In this case, the control is carried out automatically according to the algorithm (Figure 4).

The $G_{+1}$ area (Figure 3) is characterized by over-oxidation of sulphides due to the high consumption of technical oxygen from the blast per ton of charge materials, as well as an increase in the height of the smelting bath due to the high furnace productivity which can lead to the release of the smelt in the uptake and melt tuyeres. In this case, the control in the automatic mode is stopped, the manual control mode is activated, and the process is carried out with a decrease in the consumption of charge materials and the consumption of technical oxygen blast per ton of charge materials ($m^3/t$) until reaching the $G_0$ area.

4. Control algorithm for the determination of copper content in matte

All the information obtained regarding the values of the measured current smelting parameters is displayed on the automated workplace (AWP) 9 of the operator. The operator, guided by the relevant technological regulations and one's own experience in relation to the current production and technological situation, selects one of two modes of Vanukov process control: “automatic” or “manual”, selecting the appropriate control mode in the switching unit 7.

When the operator selects the “automatic” control mode, data from information transfer channels 10-18 (and others not considered in this paper) is delivered to the model to quantify the copper content in matte, developed using fuzzy logic methods. Depending on what value of copper content in the matte will be calculated by the model, either the process is carried out without changing the control settings or the recalculation and change of the control settings is made.

When the operator selects the “manual” control mode, data from information transfer channels 10-18 (and others not considered in this paper) is sent to the automated workplace (AWP) 9 of the operator.
The obtained data on the current state of the Vanukov process serves as a basis for the operator to select control settings. If the tolerance of the system exceeds 10%, the model should be retrained.

**Figure 4.** Block diagram of the algorithm for controlling the process of autogenous melting of copper-nickel sulfide raw materials in the Vanukov furnace

5. **Testing the performance of the proposed algorithm for controlling the copper content in matte**

In order to evaluate the efficiency of the developed algorithm for controlling the process of smelting copper-nickel sulfide raw materials in a Vanukov furnace, a numerical experiment was performed on the model. The experiment was carried out in three stages.

At the first stage, on the basis of the operational control data, the copper content in the matte was calculated using the quantification model for the copper content in the matte and $C_m$ compared with the set (desired) one $C_d = [59; 63] \%$.

At the second stage, based on the data of operational control and the magnitude of the mismatch calculated on the basis of the model and the specified copper content in the matte, $C_d$ the settings for the magnitude of control actions — consumption of charge materials (t/h) and consumption of technical oxygen per ton of charge materials — were calculated (m$^3$/t matte).
At the third stage, based on the operational control data, taking into account the change in the consumption of charge materials and the consumption of technical oxygen per ton of charge materials for the same point in time, the copper content in matte was again calculated.

Figure 5 presents the results of numerical simulation.

![Figure 5](image)

**Figure 5.** Results of numerical simulation of control of copper content in the matte.

1 – actual value, 2 – simulation result

As it follows from Figure 5, the change in the consumption settings of charge materials and the consumption of technical oxygen per ton of charge in accordance with the developed algorithm led to the stabilization of the copper content in the matte within the specified limits. Thus, the experiment carried out makes it possible to recommend a control system for the determination of the copper content in matte to be used in industrial conditions.

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