Development of an optimal control system for smelting process in the molten-pool

Abstract. The paper discusses the problem of controlling a complex object in the field of metallurgy, in the form of Vanyukov furnace. On the basis of literature survey authors proposed for predictive control.

Streszczenie. pracy omówiono zagadnienie sterowania złożonym obiektem z zakresu hutnictwa, w postaci pieca Vanyukova. W oparciu o analizę materiałów literackich zaproponowano własny model na potrzeby sterowania z prognozowaniem. (Opracowanie systemu sterowania optymalnego procesu wytapiania w jeziorku metalu).

Keywords: optimal control, smelting process, molten pool.
Słowa kluczowe: sterowanie optymalne, proces wytopu, jeziorko metalu.

Introduction
The smelting method of sulphide concentrates in a liquid bath in plant conditions for the first time was tested at Podolsk tin plant under the auspices of A.V.Vanyukov in 1956.

As a control object, the Vanyukov furnace belongs to the class of complex, multidimensional non-steady objects and it is extremely difficult to provide its efficient and trouble-free control. Currently, smelting process control in the Vanyukov furnace at Balkhash copper smelting plant is carried out by a shift foreman or an operator based on the experience and subjective analysis of control and measuring instruments readings (pressure and consumption in air, oxygen and gas supply systems, consumption and temperature of cooling agents, etc.), visual observation data (melt level, melt temperature, charging system conditions, etc.), chemical analysis results received with a big delay and other data from operative personnel about conditions of individual process components, and also based on preliminary calculations of material and heat balances.

It should be noted that so far there has been no optimal process control system in any Vanyukov furnace unit which in the first place is due to the lack of adequate mathematical models of the process in question.

For many years, studies of processes that take place during smelting in a liquid bath were carried out quite actively both in the former USSR and abroad. In the following years, studies of this technology continued in Russia and Kazakhstan. However, problems of a mathematical description of physical and chemical processes that take place during smelting in a liquid bath considerably fall behind the studies conducted using laboratory and actual tests of the technology which is associated with a high complexity of this technology.

Since 1980 till the end of 1990-s, quite active studies of mathematical modeling of pyrometallurgical processes in general and the Vanyukov process in particular had been carried out, but after 2000 the number of publications on this subject was considerably reduced. Analysis of the published papers showed that the authors [1] and [2] were the most successful in making the mathematical model for Vanyukov processes. While the model structure describing hydrodynamic and kinetic characteristics of chemical reactions in the region above the tuyere was developed, its identification and computer implementation were not completed [1]. Static models were also developed to monitor internal phase characteristics as the melt moved down from the tuyere level [2].

Analysis of the physical and chemical features of the Vanyukov process showed that technological efficiency of the unit was characterized by the history and intensity of the mass and heat exchange processes which resulted from interaction in the melt of the sulphide raw material being loaded onto the melt surface with blast oxygen supplied through the side tuyeres into a melt layer. Motion characteristics of the matte and slag phase flows allow us to distinguish two main zones: bubbling (intensively mixed by blast), reaction zone above the tuyere and relatively quiet zone of matte-slag emulsion breakdown and forming of external matte phase located below the tuyere plane – zone below the tuyere.

Chemical reactions in Vanyukov furnace
Let us consider the zone above the tuyere where such Vanyukov furnace processes as smelting and burden constituents merging, dissociation of higher sulphides and oxidation of the produced sulphides and sulphur take place at the same time with great amount of heat released which determine an autogenous level of the smelting process.

Dissociation and oxidation processes in the zone above the tuyere are fully characterized by the following reactions:

\[
\begin{align*}
FeS_2 \Rightarrow FeS + \frac{3}{2} S_2, \\
CuFeS_2 \Rightarrow \frac{1}{2} Cu_2S + FeS + \frac{1}{2} S_2, \\
S_2 + 2O_2 = 2SO_2, \\
FeS + \frac{3}{2} O_2 = FeO_2 + SO_2, \\
FeS + 3(Fe_2O_3) = 10FeO + SO_2, \\
3FeO + \frac{1}{2} O_2 = Fe_3O_4.
\end{align*}
\]

Apart from the matte, slag and gas phase products produced during smelting which influence the amount of heat released, it is necessary to take into account the dissociated sulphur oxidation reaction by the melted slag:

\[
2(FeO) + \frac{3}{2} S_2 = 2[FeS] + SO_2.
\]

Due to the balance of reaction components (5) a portion of the elementary sulphur is oxidized and falls into gas phase, this must be considered during heat balance calculation. The elementary sulphur is oxidized in the tuyere flame according to the reaction (1) and by the melted slag
according to the reaction (5) and also according to the magnetite reduction reaction within bath volume by the dissociated sulphur (6). The balance is achieved because the sulphur oxidation to SO2 is carried out before the equilibrium ratio between them has

\[
\frac{1}{2} S_2 + 2(FeO) = 6(FeO) + SO_2.
\]

Given the assumptions, the authors [1] presented a mathematical model of processes occurred in the zone above the tuyere of the Vanyukov furnace using the set of differential equations of material and heat balances with reactive compounds of matte, slag and gas phase determined by relations between compound concentrations in incoming and outgoing flows according to the reactions (1) – (6) and conditions of the perfect-mixing reactor.

**Mathematical model of Vanyukov furnace**

The mathematical model of the zone above the tuyere of the Vanyukov furnace proposed in [1] as compared to the available static conditions calculation model reflects the dynamic characteristics of physical, chemical and heat engineering processes of the zone above the tuyere of the unit, in addition, it includes the dynamic interactions of products (matte, slag) produced during smelting and evaluates the magnetite flow reduced by the dissociated sulphur by including reactions (5), (6) into the system. This will take into account heat release variation, and therefore, variation of heat balance structure under equilibrium conditions in the matte-slag-gas system.

Thus, the results obtained in [1] make it possible to model processes in the zone above the tuyere of the Vanyukov furnace which describe kinetic characteristics of chemical reactions considering incoming and outgoing flows of original substances and resultants. However, these relations do not consider hydrodynamic conditions in the region and do not describe phase separation processes in the zone below the tuyere.

In contrast, studies performed in [2] include well-described hydrodynamic conditions in the tuyere zone and in the zone below the tuyere, however, relations that describe kinetic characteristics of the current reactions are not given. In addition, the model [2] does not describe dynamic characteristics of the process. But the results obtained in [2] allowed the authors to find optimum conditions in the available Vanyukov furnaces and also to predict new technology conditions.

Given the abovementioned advantages and disadvantages of the models [1] and [2], we propose to combine main equations from these two papers by adding equations for correlation of the models.

Since the sulphur flow for the reaction (5) - \( \Phi_1^{(5)} \) is a sulphur mass flow, to keep up dimensionality of the equations (7), (8) and (9) given in [1], rewrite them as follows:

\[
\frac{dC_{FeS}}{dt} = \frac{1}{V \rho} \left( \Phi_{111}^{(5)} - K^* \Phi_{O_2} \frac{M_{FeS}}{3M_{O_2}} + \Phi_{111}^{(5)} \right)- \Phi_{111}^{(5)} \frac{4M_{FeS}}{3M_s} \Phi_{S} - K^* C_{FeS} \Phi_{O_2}.
\]

\[
\frac{dC_{FeO}}{dt} = \Phi_{RX} \Phi_{O_2} + \Phi_{O_2} \frac{2M_{FeO}}{3M_{O_2}} - K^* \Phi_{O_2} \frac{6M_{FeO}}{M_{O_2}} \]

\[
\pm \frac{M_{FeC}}{M_s} \Phi_{S} \Phi_{O_2}^{(5)} \pm \frac{10M_{FeO}}{M_{FeC}} C_{FeS} \Phi_{O_2}.
\]

The heat balance of the zone above the tuyere is described by a differential equation that determines heat variation of the reactive zone as a difference between incoming and outgoing heat flows, and described by the corresponding equation from [1] which we adopted without changes. All the rest of model equations from [1] and [2] are also original.

The main optimization problem is to calculate such a process control mode which would provide the selected objective function with an extreme value (minimum or maximum). And it is necessary to follow some technological

\[
\frac{dC_{FeS}}{dt} = \frac{1}{V \rho} \left( \Phi_{111}^{(5)} - K^* \Phi_{O_2} \frac{M_{FeS}}{2M_{O_2}} - \Phi_{111}^{(5)} \frac{M_{FeS}}{4M_{FeS}} \Phi_{S}^{(5)} \right),
\]

where: \( V \) - volume of the zone above the tuyere; \( \rho \) - density of the matte-slag emulsion; \( \Phi_{111}^{(5)}, \Phi_{111}^{(5)}, \Phi_{111}^{(5)}, \Phi_{111}^{(5)} \) - flows of corresponding components supplied to the zone above the tuyere with products being loaded (furnace charge, converter slag and others); \( \Phi_{O_2} = \Phi_{O_2} \Phi_{O_2} \) - flow of blast oxygen in the zone above the tuyere; \( \Phi_{O_2} \) - oxygen density; \( \Phi_{O_2} = \Phi_{O_2} \Phi_{O_2} \) - oxygen flow for smelting; \( \Phi_{S}^{(5)}, \Phi_{S}^{(5)} \) - sulphur flows for the reaction (5) and \( FeO_4 \) for the reaction (6); \( \Phi_{111}^{(5)} \) - flow of ferrous sulphide delivered by matte into the zone above the tuyere; \( \Phi_{111}^{(5)} = V \cdot \rho \Phi_{O_2} \Phi_{K_2} \) - flow of matte delivered into the zone above the tuyere; \( \Phi_{S}^{(5)} \) - sulphur volume ratio of matte in the emulsion; \( K_2 \) - delivery rate of matte into the zone above the tuyere; \( \Phi_{111}^{(5)} \) - flows of charge and slag; \( K^3, K^4, K^6 \) - coefficients of oxygen distribution in the reactions (1), (2), (4); \( K^6 \) - reaction (3) rate constant; \( C_{FeS}, C_{FeO}, C_{FeO_2}, C_{FeS}^{(5)}, C_{FeO}^{(5)}, C_{FeO_2}^{(5)} \) - concentration of components in the zone above the tuyere, furnace charge and slag respectively; \( M_{FeS}, M_{FeO}, M_{FeO_2}, M_{FeS}, M_{FeO}, M_{FeC} \); \( S_2 \) - molecular weight of FeS, O_2, FeO_3, FeO, O.

In the equation of material balance with matte it is necessary to take into account that copper matte comes out of the furnace bubbling zone in two flows: matte sedimentation in the form of large drops into the zone below the tuyere (flow \( C_{FeS}^{(1)} \)) and carry-over of a part of the matte drops which have not yet been coalesced with the slag (flow \( C_{FeO}^{(1)} \)). The values of these flows can be determined by the formulae (15) and (17) from the paper [2], then the equation for calculation of the matte amount in the tuyere zone can be presented as the following formula:

\[
\frac{dM_{FeS}}{dt} = \Phi_{111}^{(5)} (C_{FeS}^{(5)} + C_{FeS}^{(1)} + C_{FeS}^{(1)}) - \left( \Phi_{111}^{(5)} + \Phi_{111}^{(5)} \right) \frac{M_{FeS}}{M_{FeC}},
\]

The heat balance of the zone above the tuyere is described by a differential equation that determines heat variation of the reactive zone as a difference between incoming and outgoing heat flows, and described by the corresponding equation from [1] which we adopted without changes. All the rest of model equations from [1] and [2] are also original.

The main optimization problem is to calculate such a process control mode which would provide the selected objective function with an extreme value (minimum or maximum). And it is necessary to follow some technological
restrictions to ensure stable and trouble-free control of the process.

The mathematical model (7-10) with corresponding equations from [1] and [2] allows us to calculate copper losses with the dump slag in relation to productivity, chemical and physical properties of the original furnace charge, blast consumption and the oxygen amount contained in it, maintaining manometric conditions, etc. Therefore, the optimization problem description can be formulated as follows:

“To calculate such values of blast consumption for the charge mixture given, its oxygen content and charge composition which would provide minimum copper losses with the dump slag under the technological restrictions for: charge consumption, temperature in the furnace, blast consumption, oxygen content in the blast”.

Copper losses with the dump slag are determined by the quantity of matte drops which have not yet been coalesced with the slag (flow).

This type of description of the optimal control problem will enable, firstly, to control the process optimally (minimization of the copper content in the dump slag), and secondly, to conduct the process in stable and trouble-free conditions (by following the technological restrictions).

**Vanyukov furnaces automatic control system**

The “Sistemotehnika” JSC implemented the automatic process control system of the metallurgical complex with Vanyukov furnaces at Balkhash copper smelting plant. The automation object includes the following units and aggregates: the Vanyukov furnace, water-jacket cooling system of the furnace (primary and secondary circuits), continuous-handling system to supply furnace charge and coal, two oxygen-air blast systems, slag mixer, matte mixer, dust-exhaust systems of the mixers, gas cooler, deaerator, gas path.

The automatic process control system of the Vanyukov processes has a traditional three-level structure where the lower field level includes different instrumentation and shut-off and control valves. The middle technological level is implemented as a monitoring and control system without a panel board. The hardware-software basis of this level is represented by Siemens programmable logic controllers and STEP 7 system of tools. The technological level provides acquisition of information about process state, implements logics of locking actuation and output of control actions. The upper (operator) level is implemented on the basis of SCADA-system. The software of the automatic process control system of the Vanyukov processes consists of three application software systems.

Thus, excellent prerequisites for implementation of the optimal control system of the Vanyukov furnace were created, with the lower infrastructure formed the only thing to be done is to develop appropriate models and algorithms. This will allow us to implement the optimal control system with minimum costs required for its hardware.

**Conclusion**

Generally, To create the optimal control system it is necessary to identify the model (7-10) and check its adequacy, in this respect we propose to conduct appropriate research works at Balkhash copper smelting plant.

It can also be widely used when creating complex control systems (which undoubtedly include optimal control systems for melting facilities). Currently, artificial intelligence technologies are not used in the former USSR and beyond to control metallurgical objects due to their extreme complexity and difficult operation conditions for measuring instruments. However, these very reasons which obstruct implementation of traditional optimal control systems for such processes must stimulate the active usage of modern methods of the artificial intelligence theory to control melting facilities. Intelligent systems could significantly reduce the influence of the so-called human factor during control of complex objects including metallurgical objects.

However, the most efficient way is to use artificial intelligence technologies in combination with classical process control methods (so-called hybrid systems). In this case, we manage to combine advantages of traditional methods, techniques and algorithms (such as mathematical modeling, optimal control algorithms, synthesis of local control systems, etc.) with mathematical tools of the artificial intelligence theory [3-10].

**REFERENCES**