Experimental and analytical description of the electric arc furnace processes in creation of computer simulator

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Abstract
Experimental and analytical basics for building of mathematical description for metallurgical processes in the smelting of steel in electric arc furnaces, focused on the use in computer simulators for the personnel, are developed.
Keywords: ELECTRIC ARC FURNACE, PROCESSES, EQUILIBRIUM, EXPERIMENT, DATA, MODELING

Introduction

The modern trends in the steelmaking processes control orient for creating of conditions of systematic staff training in the training exercise form to ensure the work quality of steelworkers.

Development of steelmaking production is associated with the formation of conditions for automation of industrial processes and is aimed at increasing the performance and technical and economic characteristics of heats. There is a considerable contradiction between the very high level of processes information security and, by no means, low degree of computer systems use for melting process control in conditions of steelmaking production. Therefore, steelworkers are usually based only on their experience, knowledge and intuition in decision-making, which is often does not lead to the best performance in terms of electricity consumption and rational consumption of raw materials [1].

The simulator project development in the form of automated process control system (APCS) of steel smelting, will allow steelmaker-operators to learn how to make the right decisions, relying not on intuition but on data modeling process.

Steelmakers exercise training using specialized computer simulator, which imitates the metallurgical processes of steel smelting, will allow to form the practical decision-making skills for process control and to visually demonstrate the essence of the processes occurring in the system [2].

Problem statement

Let's formulate the basic requirements for product of the project – automated system of education and training of arc furnace steelmakers:

- purpose: the development of steelworkers thinking and skills acquisition of effective process control;

- form of the product: a computer simulator, including informational - reference system and educational subsystems of the knowledge automated control using the tests, training exercises, and the results displaying;

-the development opportunity: the system has an open architecture and provides the possibility of expanding with a connection of other subsystems for training of the metallurgical enterprise technological staff.

Connection of problem with the important scientific and practical tasks

Steelworker task is to conduct the smelting process in compliance with the technological regime norms for the steel production with specified quality and with the lowest technological costs [2]. The target function, which determines the efficiency of adopted decisions about the process control can be determined by the actual production data or on the basis of mathematical modeling [3]. The composition of raw materials for smelting and the characteristics of the smelting furnace vary from heat to heat. In this formulation of the control problem steelmaker can use as a process control actions not only a set of process operations, which modify the equilibrium state of the system "metal - slag", but also the qualitative parameters - substances used in the individual process stages [4].

The structure of the software is built in a hierarchical manner. The learner has consistently passed the corresponding levels of training with getting the acquaintance knowledge, playback knowledge, skill knowledge and in the last stage with the help of training simulator should reach the creation level of knowledge, which will allow a steelmaker to make the decisions, both in-house as well as in emergency situations. The project implementation of smelting furnaces staff training on the simulator is the first step in the implementation of ACS TP using the computer technologies for process control and decision support. The most important component of a computer decision support system for the control of electric arc furnaces and simulation software system is a subsystem of calculation of chemical equilibrium and material balance, which is designed to determine the results of the technological process in the course of melting depending on the type and weight of the components, which are loaded into the furnace in the individual process stages [5].

The methods for calculating the composition of the metal in the furnace bath, which applied in practice, are based on the use of experimentally determined coefficients "melting loss" or "recovery" of slag forming, alloying and deoxidizing materials [6].

This approach allows to determine the mass of the reactants approximately, which leads to unnecessary consumption of materials and increase of the duration of the process due to the need of additional adjustments in the metal composition in the furnace bath. [7]

The article aim formulation

The aim of the study is to develop a mathematical description of the steel smelting technological process in electric arc furnaces based on the decomposition performance, including the metal melt, slag, walls and hearth of the furnace and the furnace atmosphere.

The mathematical description of the process

The process of steelmaking in the electric arc furnace is carried out on a periodic circuit, which comprising a mixture metal part loading and slag-forming components, mixture melting, conducting of oxidation and reduction periods, operations of refining and adjusting the composition of the molten metal before the release [4].

A mathematical model of the steelmaking process should reflect the changes in the composition of the molten metal, slag and furnace linings influence on the final results [5]. Generally it is necessary to consider the following system elements: metal, slag, and the furnace atmosphere and lining [8] (Fig. 1).

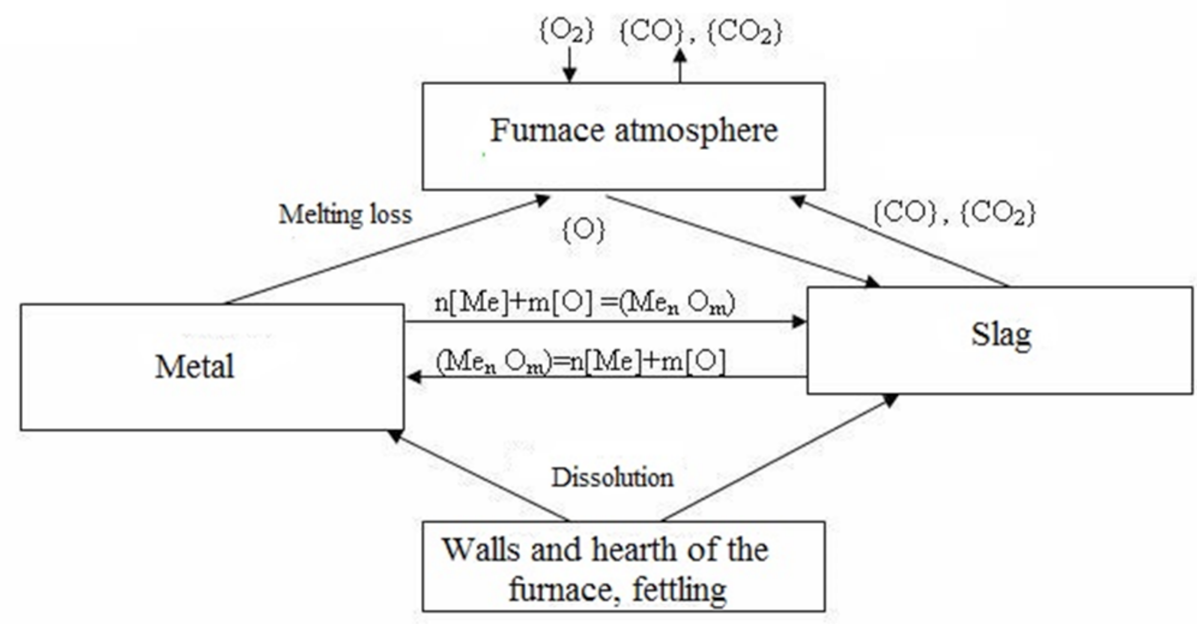

Figure 1. Steelmaking furnace interacting elements

The furnace material balance equation as an ideal mixing aggregate of batch action. Thus it is possible to consider the metal and slag as separate interacting systems

$$\frac{dx_i}{dt} = -W_i + r_i - u_i$$
$$\frac{dx_s}{dt} = -W_s + r_s \qquad (1)$$

where *x* – is the concentration of the components in the metal (*i=1, 2, ..., k*) and slug (*s = 1, 2, ... , m*), %; *W* - the rate of chemical reaction, s^{-1}; *r* – is the rate of components dissolution of the lining and fettling, s^{-1}; *u* - the rate of mixture and smelt loss under the influence of electrical arc, s^{-1}; τ - is the residence time of the components in the system.

The furnace energy balance equation:

$$(m_{Me}c_{Me} + m_{sl}c_{sl})\frac{dT}{dt} = m_{Me}\sum_{j=1}^{k+m} W_j(-\Delta H_j) - \sum_{l=1}^{h} Q_l + P \qquad (2)$$

where m_{Me}, m_{sl} – are the mass of metal and slag in the furnace bath, kg; c_{Me}, c_{sl} – are the heat capacity of metal and slag in the furnace bath, J/(kg K); ΔH – is the enthalpy of chemical reactions, J/kg; Q - is the rate of heat removal from the system by cooling the vault, the heat transfer through the outer surface of the furnace, with flue gases of the furnace, etc., J/s; *P* – is the heat capacity of the furnace, J/s;

The equations of kinetics and equilibrium of metallurgical reactions

Due to the fact that the known kinetic dependences do not properly reflect the specificity of metallurgical processes, the empirical formula for describing the carbon oxidation kinetics in the work [6] is adopted.

This dependence is obtained on the basis of experimental data for furnace DSP-3M under the assumption that the carbon oxidation is held by the reaction of the first order

$$-\frac{dC}{dt} = kC, \qquad (3)$$

where *C* – is the carbon concentration, %; *t* – is the time, min.

After integrating of the above mentioned equation we obtain: $C = C^{init}e^{-kt}$

Fig. 2 compares the experimental data (Emp) for the three test heats with the calculated values (dC). The equation resulting in the passive experiment is applicable to the type of furnace DSP-3M with acid lining under the following conditions: the process temperature – 1540 — 1630 °C , consumption of iron ore pellets 0,6 — 0,8 kg per ton of metal at each loading.

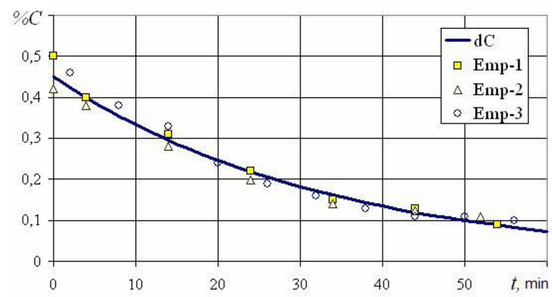

Figure 2. Comparison of empirical and calculated data

During the experiment, a new portion of pellets was added in the bath, after boiling of metal began to reduce. Therefore, the resulting equation, in general, is not the kinetic dependence. It shows the character of the carbon concentration change during the oxidation period in real conditions of production in compliance with the requirements of technological regulations.

All other reactions reach the equilibrium except the carbon oxidation. Such an assumption is acceptable because all processing steps are completed, usually with 5-10 minute pause-delay, which is necessary to equalize the steel components concentrations in the bath and the removal of dissolved gases in the metal and oxides [4].

The general model also includes the empirical relationships between the different parameters of the process: the distribution of sulfur between slag and metal [4], oxidative ability of various deoxidants [6], the average cooling rate of the furnace in case of arc disabling.

Besides the limitations on the parameters, which are taken into account in the simulation, are considered. A limitation of application field of the process of mathematical description is the transition temperature of the metal in the solid state $T > T_{kr}$, due to the fact, that metallurgical conversions in steel smelting are held in a molten metal. The second limitation is the capacity of the furnace. The weight of mixture fettling in tones must be within the $1,2 \leq G \leq 4,5$.

During the loading of low mass mixture, the intensive influence on the electric arc on the furnace hearth material, which leads to the destruction of the lining, takes place. However, the excess of mixture mass permissible load leads to the fact that obtained results will not meet the reality, because the furnace cannot accommodate a greater volume of metal by its design characteristics.

The initial conditions for each of the j-th stage of the process, excluding the initial loading of the mixture metal part and slag forming components will be as follows:

$$\begin{aligned} t_j &= 0; \\ X_j &= X_{j-1}; \\ G_j &= G_{j-1}; \\ S_j &= S_{j-1} \\ T_j &= T_{j-1}; \end{aligned} \qquad (4)$$

where t – is the time, min; X – is the components composition of the liquid metal in the furnace bath, %; G – is the mass of liquid melt in the furnace bath, kg; S - the composition of slag components, %; T – temperature, °C; j – process number: loading (0), mixture smelting (1), oxidation (2), reduction (3), refining operations (4) and the adjustments of molten metal composition before the release (5).

At steady state, it is assumed that in the entire volume of the furnace bath the temperature is the same. Thus in the furnace the two systems are formed, which are in equilibrium: the metal melt and slag [5]. In each of these systems the concentrations of elements are the same, but not equal. That is, for example, the silicon concentration in the entire volume of melt is the same, but the silicon in the slag is in the form of SiO_2, and its concentration differs from the silicon concentration in the smelt. The number of freedom degrees of mathematical description equations system is defined as the difference between the number of variables and the number of equations linking them [5]. Full mathematical description includes 199 variables occurring in the 161 equations. Accordingly, the number of degrees of freedom is 38. From these variables must be subtracted:

- 21 process conditions variables and specified data at the beginning of the calculation;
- 6 variables, which are characterizing the composition of the refractories;
- 12 variables, which are characterizing mixture melting loss, dissolution characteristics of the furnace and hearth fettling;
- 3 variables, which involved in the oxygen balance calculating - namely, the area of a molten metal mirror, the rate of oxygen absorption from the furnace atmosphere and the degree of limestone melting.

The result is 2 degrees of freedom and, accordingly, 2 variables that must be set – are the furnace transformer capacity and time, as well as 15 variables, which are basic components of metal and slag, which are determined, based on the furnace filling data. This is the control parameters of each stage. The control of these parameters allows to lead the smelting by furnace staff.

Conclusions

Using the principle of steel smelting process decomposition in electric arc furnaces at the stage allows to pass to the typical models of individual stages in the ACS TP building, as well as training programs for steelmakers. An important feature of the proposed approach is the ability of its implementation in production conditions. Since for making the informed technological solutions the results account of the simulation of individual process steps in addition to the used parameters are expected. The use of modern computer facilities to support the decision-making within the ACS TP, as well as in the training systems, allows to eliminate the computational constraints and to perform the calculation of the process parameters on the basis of experimental and analytical dependences.

The above method of interaction account of the steelmaking furnace elements and the use of real experimental data for the calculation by obtained empirical dependence of the carbon oxidation kinetics allows to carry out the multiple calculations of material balance of heat.

The obtained results can be used for the building of automated process control system, and it will also be useful in the design of computer simulator for electric arc furnace steelmakers.

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