Study of transition processes of blast-furnace smelting by the mathematical model method

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Abstract. In work possibilities of the developed computer model system for forecasting of a thermal condition of a blast furnace (on change of the maintenance of silicon in pig-iron) in a mode of real time are considered. The basis of the model is the fundamental knowledge of the theory and practice of the modern blast-furnace process, the use of regularities in the processes of heat and mass transfer, gas dynamics, slag formation processes in modern blast furnace melting. When solving the dynamic problem, it is envisaged to use the analytical (obtained on the basis of fundamental knowledge), but the linearized model of the domain process, the principle of small deviations and the natural-mathematical approach. In the algorithm for solving problems in transient blast furnace processes, the calculation of the dynamics of the change in the heating of the bottom of a blast furnace (based on the silicon content in cast iron) was performed according to the additivity rule by summing the predicted silicon concentrations in cast iron when the loading parameters (ore load) and the control actions on the thermal load the state of the furnace from the bottom - the consumption of natural gas, the concentration of oxygen in the blast and the humidity of the blast. Examples of calculations of the transient processes of the gas-dynamic resistance of the batch layer, the thermal state, and the productivity of the blast furnace are shown in the context of the changes in the properties and composition of the iron-ore materials being loaded and the parameters of the combined blast are applied to the conditions of PJSC “Magnitogorsk Iron and Steel Works” (MMK).

1. Introduction

The paper investigates transition processes of blast-furnace smelting using analytical and theoretical models describing regularities of heat and mass transfer with consideration of kinetics of processes proceeding in the blast furnace; by methods of passive and active experiments, according to the data of blast furnace operation with the use of statistical methods as well as based on results of specially setup experiments or by selecting significant periods of normal blast furnace operation containing input signals of the required type. Each of these directions has obvious advantages and disadvantages widely described in scientific literature [1–17].

Analytical models based on physics of the processes enables to theoretically evaluate the nature of dynamic characteristics of the processes in any conditions of blast-furnace smelting without interferences [1, 10–13]. However, complexity of blast-furnace smelting processes, problematical character of the complete description of the processes, complexity of the mathematical solution of the differential equation system does not allow the developed models to fully consider characteristics of the processes. Data on actually used dynamic analytical models of this class over the last years are not virtually available.
It should be noted that the common regularity summarizing the results of mathematical modelling of unsteady heat transfer processes in the layer consists in an aperiodic (non-oscillatory) response of transition processes [14, 15]. However, this provision is only valid if the ratio between thermal capacities of material and gas flows along the height of the concerned area of the layer is fixed, which does not reflect development of heat transfer processes along the height of the blast furnace. Due to the above, the results of modelling of unsteady heat transfer processes in the layer considering thermal effects of reduction processes give a quantitative estimation of transition process duration and a general idea about the nature of transition processes only in particular areas of the layer but not for the blast furnace as a whole.

2. Description of dynamic model for blast-furnace process

The dynamic model intended for prediction of blast-furnace smelting progress in a real-time mode is based on fundamental theoretical and practical knowledge of the modern blast-furnace process, use of regularities of heat and mass transfer processes, gas dynamics, slag generation processes in modern blast-furnace smelting. In addition, mathematical, algorithmic and program software developed earlier by the authors of the paper for blast-furnace smelting control is widely used [16-20].

For solution of the dynamic problem, an analytical (based on fundamental knowledge) and linearized model of the blast-furnace process, principle of small deviations and natural mathematical approach shall be used [21]. In this regard it is necessary to assess preliminarily the range of input parameter variation against the underlying value within which the coefficients of the dynamic model can be taken as constant [16].

Dynamic modelling of the blast-furnace process was performed in a specific sequence. Using the averaged data of blast furnace operation in the basic period (10 hours), the following parameters are calculated:

- blast-furnace burden, including the specific rate of coke and iron-ore materials for both basic and predicative options [22]. The specific output of slag and slag composition as well as flux flow rate at a given slag basicity and slag properties are determined;
- set of parameters characterizing gas dynamic conditions of blast-furnace smelting [16, 17];
- arrangement and configuration of the softening and melting zone of iron-ore materials [18];
- coefficients of transfer along different exposure pathways for performance of factor analysis using URFU’s algorithm; application areas of linearized models are assessed using methods presented in papers [16, 17];
- time from the start of burden charging to the moment when burden reaches the tuyeres (time of one burden cycle) [17, 22, 23];
- transition processes of gas dynamic resistance in the upper and lower zones of the burden layer when the composition and properties of iron ore burden are changed;
- transition processes of blast-furnace smelting for different exposures: change of ore load, natural gas flow rate, blast humidity and temperature, oxygen content in blast as well as blast-furnace slag basicity;
- in accordance with variation of basic parameters in time in the design period, prediction of gas dynamic and heat conditions of blast-furnace smelting in real time is made for duration of the design period equal to 8 hours.

Considering the hypothesis of linearity of the object in question, the reaction of the system to any sum \( n \) of input exposures can be calculated as per following equation:

\[
\Delta[S](t) = \sum_{j=1}^{n} \int_{0}^{t} h_{ij}(t - \tau) \frac{dX_{\alpha j}(\tau)}{d\tau} d\tau,
\]

where \( \Delta[S](t) \) is a variation of increment in [Si] with time; \( h_{ij}(\tau) \) is a transition function of the system for \( j \)-th exposure; \( X_{\alpha j}(\tau) \) is a variation of the increment time of \( j \)-th input exposure.
The delay time when properties and flow rate of burden materials are changed is taken equal to the time of one burden cycle. To determine the type of the transition process (aperiodic, oscillatory, readjustment value), the calculation results of transition processes as per mathematical model presented in the papers were used [14, 15].

3. Calculation results of transition processes using dynamic model

Calculation examples of transition processes of gas dynamic resistance in the burden layer, thermal state and blast furnace performance with changes in properties and composition of charged iron ore materials and parameters of combined blast are made in relation to conditions at Magnitogorsk Iron and Steel Works (MMK).

Dynamics of the lower gas pressure drop along the height of the burden layer with a bigger portion of pellets in the iron ore part of the burden is shown in figure 1, a. As the temperature range of melting for nonfluxed pellets is wider than for fluxed agglomerate, an increase in the portion of iron ore pellets in the burden of the blast furnace will be accompanied by growth of gas dynamic resistance in the cohesive zone. Addition of agglomerate with a bigger content of fines will be accompanied by growth in the upper gas pressure drop along the height of the layer (figure 1, b). The growth in the upper gas pressure drop along with the growth in the total pressure drop will be observed immediately after charging burden with a bigger portion of fines in agglomerate and will continue up to arrival of this burden in the slag formation zone, i.e. in a melting time of one furnace volume.

![Diagram](a)

![Diagram](b)

**Figure 1.** Change in gas pressure drop along the height of the burden layer:

- a – when the portion of pellets in the iron ore part of burden is increased from 0.34 to 0.54 t/t;
- b – when the content of fines in agglomerate (0-5 mm fraction size) is increased from 6.1% to 10.8%.

When ore load is changed, the start of a change in furnace performance over time corresponds to changing of one burden volume in the furnace (figure 2, a); the transition period time is approximately equal to the same period. A change in intensity of melting products heating characterized by silicon
content in hot metal starts in a period of time which lasts one burden cycle in the furnace and the total time of the transition process up to a new value of silicon content is 3 to 3.2 burden cycles.

A change in the natural gas flow rate and oxygen content in blast causes an alternating nature of Si content change in hot metal (figure 3). This is stipulated by almost instantaneous impact of these parameters on changing the thermal level in the furnace hearth and by inertia influence on reducing and heating processes. At the initial time, when the natural gas flow rate decreases due to an increased temperature in the hearth, which is related to reduction in heat input for natural gas decomposition, Si content in hot metal hot metal increases. After a certain time period equal to the time of one burden cycle in the furnace, we observe a decrease in heating of the lower zone due to increased direct reduction of iron oxides. At the initial time, after the oxygen content in blast increases, due to a temperature growth in the furnace hearth during one burden cycle, Si content in hot metal increases. However, further on we observe a decrease in heating of the lower furnace zone and decrease in Si content due to a temperature drop in the furnace stack and increased direct reduction of iron oxides. Thus, an alternating nature of Si content change in hot metal is formed for these actions.

When slag basicity (CaO/SiO₂) is increased, we observe a decreased Si concentration in hot metal. This is related to the fact that addition of the basic oxide (CaO) to slag is accompanied by binding of silicon oxide in slag into a strong entity, i.e. calcium silicate (CaO·SiO₂), where silicon reduction requires much more efforts in comparison with silicon reduction from "pure" silica. When calculating a dynamic pattern of Si content change in hot metal with introduction of disturbance due to a change in slag basicity (figure 4), we took into account that Si content change in hot metal starts in a time period equal to the time of one burden cycle in the furnace and the time of the transition period is also equal to the time of one burden cycle.

![Figure 2](image_url)

**Figure 2.** Change in furnace performance (a), silicon content in hot metal (b) when ore load is increased from 3.76 to 3.86 t/t.
With a change in blast temperature, we observe a change in heating of the furnace bottom and, as a result, a change of Si content in hot metal (figure 5). With introduction of disturbance due to a change in the blast temperature, the thermal condition of the lower furnace zone changes immediately after the change in this parameter. The time of the transition period is equal to the time of one burden cycle.
To test the model for adequacy, we made calculations with respect to operational conditions of Blast Furnace No.10 of MMK throughout the duration of 17 iron tappings (26 hours of continuous furnace operation). We selected two periods of furnace operation – at the start (first period) Si content in hot metal was continuously growing $[\text{Si}] = 0.78\%$ to $[\text{Si}] = 1.402\%$; then, in a result of decisions taken, Si content in hot metal was monotonously going down from $[\text{Si}] = 1.402\%$ to $[\text{Si}] = 0.574\%$. The specific feature of these periods is that the chemical composition of iron ore burden components and coke properties virtually remained unchanged during this period. At the same time, corrections were made in ore load, natural gas flow rate, oxygen content in blast and hot blast temperature.

Figure 6 shows dynamic patterns of main input parameters of ore load, natural gas flow rate, oxygen content in blast, hot blast temperature at a simultaneous change of input parameters and figure 7 shows a comparison between the actual and design change of Si content in hot metal for the cases under study. The comparison between the actual and design change of Si content in hot metal demonstrates a quite satisfactory concurrence of predicted and actual values of Si content in hot metal.
Thus, the suggested algorithm for solving a problem concerning study of dynamic patterns of the thermal state during smelting (by Si content in hot metal) describes the dynamics of the process state quite well with actions aimed both at furnace heating increase and furnace heating decrease.

![Figure 7. Comparison between the actual change (continuous line) of Si content in hot metal (%) and design (dashed line) values with introduction into the smelting process of parameters causing an increase and decrease of Si content in hot metal.](image)

4. Conclusions
1. The oscillatory transition process is observed in the blast furnace provided that after introduction of a disturbance into the process this disturbance will have an opposite influence on the thermal state of the lower and upper heat-exchange stages. The more the difference is in size and sign, the more the value of readjustment will be in this case.
2. The most predictable parameters influencing Si content variations in hot metal are changes in ore load as well as change in slag basicity. It is certain that Si concentration in hot metal is also determined by other factors, i.e. blast temperature and humidity. However, use of these parameters for immediate influence on heat conditions of blast-furnace smelting is limited as the blast temperature is kept at a maximum level and the change in humidity is used as a parameter to control the heat conditions of blast-furnace smelting when there are deviations from normal heat conditions.
3. It is not desirable to use a change of oxygen concentration in blast and natural gas flow rate as parameters for control of Si content in hot metal. This is related to an alternating influence of these parameters on heat conditions of blast-furnace smelting. An unreasoned decision to use the parameters of natural gas flow rate and oxygen concentration in blast for control of Si content in hot metal can lead to the opposite results.

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