Advanced Dynamic Predictive Model for Basic Oxygen Furnace Purging

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Abstract

This paper focuses on the development of a dynamic model for the purging mode in a basic oxygen furnace process, a key issue for enhancing energy and resource efficiency in modern steelmaking. The primary objective is to create a comprehensive state-space model suitable for the design of an advanced control system. The study analyzes the influence of key control parameters, namely the lance height above the quiescent bath level and the oxygen blast intensity, on the process outputs. The model describes the transient dynamics connecting these inputs to the decarburization rate and the degree of carbon oxidation to CO_2 in the converter cavity. It is established that these relationships are non-stationary and are described by first and third-order differential equations, whose parameters (time constants, process gains) were determined in this paper. By connecting these individual subsystems in series, a comprehensive state-space model in controllable canonical form was developed. This resulting model is intended for use as the predictive core for a control system.

Keywords

prediction model, control, state-space model, basic oxygen furnace

1. Introduction

The basic oxygen steelmaking process is noted for the complexity of its physicochemical phenomena, which proceed at high rates and temperatures. It is characterized by multiple operational modes and the high dimensionality of the problems to be solved. The quality of the final steel is determined by its composition and temperature. The converter can be considered a chemical reactor wherein the oxidation of various elements and the redistribution of impurities and heat between the metal and the slag occur. An investigation was conducted using data from converters with a 160-tonne capacity. The converters process hot metal with the following composition (%): silicon, 0.4–1.0; manganese, 0.3–0.6; sulfur, 0.02–0.07; and phosphorus, 0.02–0.15. The temperature of the hot metal varied within the range of 1200–1400 °C [1]. The charge included metallic scrap in quantities ranging from 0 to 30% of the hot metal's mass. Liquid hot metal was supplied from a mixer in 140-tonne ladles. The oxygen injection rate was 2.5–3.0 m³/(t·min). The assortment of steel grades produced was characterized by a carbon content of 0.09–0.40% and a tapping temperature of 1580–1630 °C. Steel smelting is an intensive process, which makes it physically impossible for the converter operator to process a large volume of information, select the optimal operating regime, and intervene in the course of the heat in a timely manner. Under manual control, the blowing process often deviates from the optimum, and slag formation is disrupted. Consequently, the slag may become either inactive or excessively foamy, leading to slopping and ejections. With manual control, only 45–50% of heats, and sometimes fewer, are successfully tapped on the first attempt [2].

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The quest for greater efficiency, quality, and consistency in basic oxygen furnace (BOF) steelmaking has driven a continuous evolution in process control methodologies. From early reliance on operator experience, the industry has progressed through successive generations of predictive models, each aiming to better capture the complexities of the high-temperature, multiphase reactions within the converter. This evolution reflects a broader shift from static, precalculated control to dynamic, data driven optimization, a journey catalyzed by advancements in both metallurgical understanding and computational technology. The first attempts to move beyond purely empirical control involved the development of mechanistic models grounded in the fundamental laws of physics and chemistry. These models sought to describe the BOF process using first principles of thermodynamics, kinetics, and mass and energy transfer.

The earliest and most fundamental form of process control model is the static model. These models are essentially a set of pre-blow calculations based on comprehensive mass and energy balances for the entire heat. Given the initial conditions, such as the weight, temperature, and chemical composition of the hot metal and scrap. The desired final (endpoint) steel composition and temperature, the static model calculates the total required inputs. These include the total volume of oxygen to be blown, the weight of fluxes (lime, dolomite) needed to achieve a target slag basicity, and the number of coolants (like iron ore) or heating agents required to hit the thermal target. Static models are often described as a feedforward (open loop) control strategy; they provide a single set of instructions at the beginning of the blow but offer no capability for in blow adjustment or correction based on the actual process evolution [3]. Their accuracy is therefore highly sensitive to the quality and stability of the input data and the validity of the underlying thermodynamic assumptions [4].

Recognizing the limitations of the static approach, researchers developed dynamic models to predict the state of the bath during the oxygen blow. Unlike static models, which treat the process as a single transformation from start to finish, dynamic models aim to describe the trajectory of key variables like bath temperature and composition over time. Early dynamic models were often based on unsteady-state mass transfer theory and sought to capture the spatial heterogeneity of the furnace by dividing it into multiple reaction zones. For example, a common approach was to model the BOF as having three distinct zones: a jet impact zone where the supersonic oxygen jet hits the bath, an emulsion zone comprising metal droplets dispersed in the slag, and a bulk slag-metal zone [5]. Static control operates under the assumption of a largely deterministic process where initial conditions fully dictate the final state. Dynamic control, in contrast, acknowledges that the process is inherently stochastic and requires real-time feedback and correction.

The true breakthrough in data-driven modeling came with the application of machine learning, which offered powerful new tools for handling complex, non-linear, high-dimensional datasets. The adoption of ML in steelmaking was not merely a matter of following a technological trend, but a necessary evolutionary step to fill the performance gap left by mechanistic models. Over the past two decades, a variety of ML algorithms have been successfully applied to BOF process control, primarily for endpoint prediction. Artificial Neural Network (ANN), and their common variants like the Backpropagation Neural Network (BPNN) and Extreme Learning Machine (ELM), are exceptionally well-suited for modeling the complex, non-linear input-output relationships found in BOF data[6]. They have been widely and successfully used to build predictive models for key endpoint parameters like steel temperature and the concentrations of carbon and phosphorus [7]. The disadvantage of using an ANN to predict BOF purging is that they are often complex 'black boxes' that require large amounts of data and significant computational resources to train. This makes them difficult to interpret and prone to overfitting.

2. Development of dynamic prediction model

In the current landscape of metallurgical industry development, pressing tasks include the development of resource-efficient steelmaking processes, the advancement of theoretical and practical aspects of novel energy-saving methods for blowing the steelmaking bath with process gas, and the enhancement of furnace thermal efficiency. One of the key approaches to reducing operational expenditures is the recovery of physical and chemical energy from converter off-gases, specifically through the post-combustion of carbon monoxide (CO) to carbon dioxide (CO_2). Control of the purging necessitates the measurement of the CO_2 mass fraction and the blowing rate. Due to the technological specificities of the process, the CO_2 content is calculated using a mass balance equation for the gases in the blast, ambient air, and the off-gas duct [8].

The mathematical model for the dynamic control of the blowing process, which is based on the distribution of blast oxygen among the molten metal, slag, and converter gas phases, is represented by a system of differential equations. These equations characterize the mass and heat balance within the converter and its off-gas. In the development of this dynamic model, gradients of the control parameters are neglected, under the assumption that spatial heterogeneity in both chemical composition and temperature is absent within the bath due to intensive mixing. The primary contributors to the process's mass transfer and energy balance are the thermochemical reactions involving the oxidation of carbon and iron from the bath. It is assumed that the converter gas, as a product of the bath's decarburization, consists of CO and CO_2. In the converter's freeboard, carbon monoxide is partially combusted to form carbon dioxide. This reaction, along with the combustion of iron, leads to a decrease in the oxygen assimilation coefficient by the carbon in the bath and lowers its burnout rate. Considering the above, the decarburization rate of the bath can be expressed in terms of the volumetric flow rate of the blast oxygen (1):

$$\frac{dG_c}{d\tau} = 10^{-3}\frac{2\cdot 12}{22{,}4}\cdot\left[v\gamma_1(1-\gamma_2) - 10^3\frac{22{,}4}{2\cdot 12}(1-\gamma_{CO})\frac{dG_c}{d\tau} - 10^3\frac{22{,}4}{2\cdot 56}\frac{dG_{Fe}}{d\tau}\right], \qquad (1)$$

where $\frac{dG_c}{d\tau}$ – is the mass rate of bath decarburization, t/min; v – is the volumetric flow rate of the blast, m³/min; γ_1 – is a coefficient characterizing the purity of the blast; γ_2 – is a coefficient characterizing blast losses; γ_{CO} – is the mass fraction of carbon from the bath that is oxidized to CO within the converter cavity by the blast oxygen; $\frac{dG_{Fe}}{d\tau}$ – is the mass rate of iron oxidation from the bath, t/min.

Let express the decarburization rate (2), considering that $\gamma_{\mathrm{CO}_2} = 1-\gamma_{\mathrm{CO}}$ and $v_{O_2Fe} = 10^3\frac{22{,}4}{2\cdot 56}\frac{dG_{Fe}}{d\tau}$:

$$\frac{dG_c}{d\tau} = 10^{-3}\frac{2\cdot 12}{22{,}4}\frac{v\gamma_1(1-\gamma_2) - v_{O_2Fe}}{1+\gamma_{CO_2}}, \qquad (2)$$

where v_{O_2Fe} – is the oxygen flow rate consumed for the oxidation of iron in the bath, m³/min; γ_{CO_2} – is the mass fraction of carbon from the bath that is oxidized to CO_2 in the converter cavity by the blast oxygen.

The oxygen flow rate consumed for the oxidation of iron in the bath is determined by the following relation (3):

$$v_{O_2Fe} = 10 m_h\gamma_s\frac{16}{72}\frac{22{,}4}{32}\gamma_{FeO}\tau_p^{-1}, \qquad (3)$$

where m_h – is the mass of the hot metal, t; γ_s – is the slag fraction relative to the metal mass; γ_{FeO} – is the iron oxide content in the slag, %; τ_p – is the average blowing time, min.

The values γ_{FeO} (4) and γ_{CO_2} (5) are functions of the lance height above the quiescent bath level:

$$\gamma_{FeO} = 16{,}34H - 5{,}63 \qquad (4)$$

$$\gamma_{\mathrm{CO}_2} = [10{,}2(H-1{,}5)^2 + 3{,}1]10^{-2}, \qquad (5)$$

where H – is the position of the lance above the quiescent bath level, m.

For a 160-tonne converter, with a slag fraction of 0.1 and an average blowing time of 20 min $v_{O_2Fe} = 10\cdot 160\cdot 0{,}1\cdot\frac{16}{72}\frac{22{,}4}{32}\gamma_{FeO}\frac{1}{20} = 1{,}244\gamma_{FeO}$. For a blast supply rate of 400 m³/min, a blast oxygen purity of 0.99, and losses of 0.01, the resulting dependency of the decarburization rate (Figure 1) on the lance position above the quiescent bath level using (2), (4) and (5) is obtained as follows (6):

$$\frac{dG_c}{d\tau} = \frac{427{,}55-21{,}78\mathrm{H}}{102(H-1{,}5)^2+1031}. \qquad (6)$$

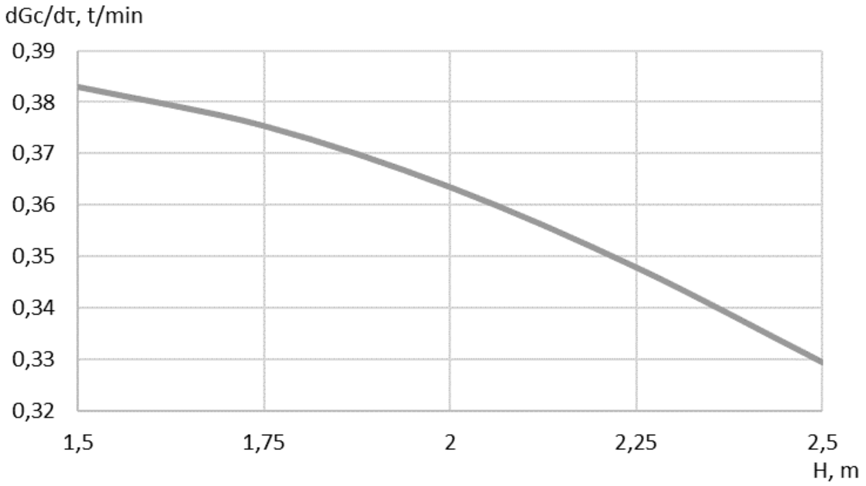

Figure 1: The effect of the lance height above the quiescent bath level on the decarburization rate

The transient process of the change in the decarburization rate $v_c = \frac{dG_c}{d\tau}$ as a function of the change in the lance height above the quiescent bath level H is described by the differential equation (7):

$$T_{v_c}^{H}\frac{dv_c(t)}{dt} + v_c(t) = k_{v_c}^{H}H(t), \qquad (7)$$

where $k_{v_c}^{H}$ – is the process gain for the lance height to decarburization rate, $\frac{t}{min\cdot m}$; $T_{v_c}^{H}$ – is the time constant, s. The value of the process gain can be found from relation (6) $k_{v_c}^{H} = \frac{\Delta v_c}{\Delta H} = \frac{(0{,}329-0{,}383)\frac{t}{min}}{(2.5-1.5)m} \approx -0{,}054\frac{t}{min\cdot m}$. Difficulties arise in determining $T_{v_c}^{H}$ due to the transient processes within the decarburization rate sensor. Therefore, to determine the time constant, impulse response characteristics and the analysis of acoustic oscillations via the measurement of gas pressure in the converter's intermediate gas duct were used [7]. The value of the time constant is nonstationary (Figure 2) and depends on the stage of the heat. This dependency is described by a third-order Gaussian function (with an R^2 value of 0.989) as shown in expression (8):

$$T_{v_c}^{H}(\tau) = 7{,}05\cdot e^{-\left(\frac{\tau-3{,}47}{2{,}9}\right)^2} + 6{,}61\cdot e^{-\left(\frac{\tau-15{,}57}{2{,}6}\right)^2} + 11{,}48\cdot e^{-\left(\frac{\tau-9{,}73}{6{,}0}\right)^2}, \qquad (8)$$

where τ – is the time from the start of the blow, min.

A change in the decarburization rate leads to a change in the degree of carbon oxidation to CO_2 in the converter cavity. This process can also be described by the following first-order differential equation (9):

$$T_{\gamma_{CO_2}}^{v_c}\frac{d\gamma_{CO_2}(t)}{dt} + \gamma_{CO_2}(t) = k_{\gamma_{CO_2}}^{v_c}v_c(t), \qquad (9)$$

where $k_{\gamma_{CO_2}}^{v_c}$ – is the process gain for the decarburization rate to degree of CO_2 oxidation, $\frac{min}{t}$; $T_{\gamma_{CO_2}}^{v_c}$ – is the time constant, s. The value of the process gain can be found from relation (2): $k_{\gamma_{CO_2}}^{v_c} = \frac{\Delta\gamma_{CO_2}}{\Delta v_c} = \frac{0{,}133-0{,}0565}{(0{,}329-0{,}363)\frac{t}{min}} \approx -2{,}25\frac{min}{t}$. According to the research results [8] $T_{\gamma_{CO_2}}^{v_c} \approx 2{,}15\ s$.

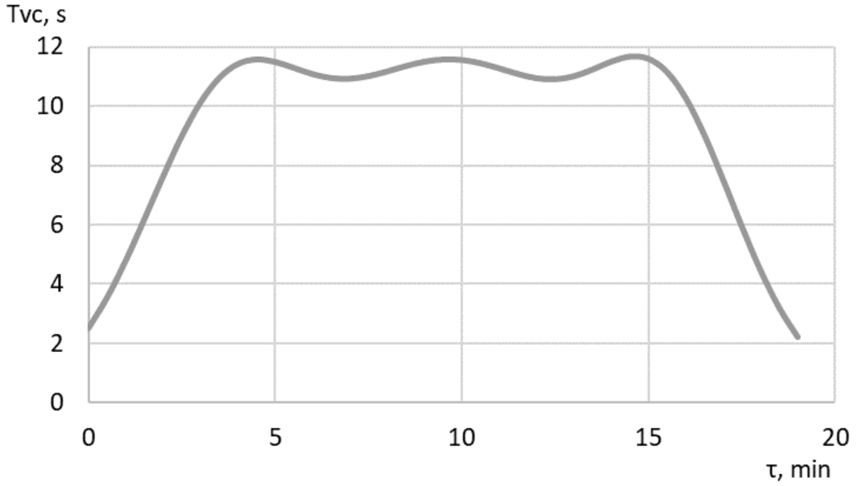

Figure 2: Dependency of the time constant on the time from the start of the purging

The transient process for the change in the degree of carbon oxidation to CO_2, resulting from a change in the lance height above the quiescent bath level, is formed by the series connection of (7) and (9) and is described by the differential equation (10):

$$T_{1\gamma_{CO_2}}^{H}(\tau)\frac{d^2\gamma_{CO_2}(t)}{d^2t}+T_{2\gamma_{CO_2}}^{H}(\tau)\frac{d\gamma_{CO_2}(t)}{dt}+\gamma_{CO_2}(t)=k_{\gamma_{CO_2}}^{H}H(t), \tag{10}$$

where $k_{\gamma_{CO_2}}^{H}=k_{v_c}^{H}\cdot k_{\gamma_{CO_2}}^{v_c}=\left(-0{,}054\frac{t}{min\cdot m}\right)\cdot\left(-2{,}25\frac{min}{t}\right)\cdot 100\%=12{,}15\frac{\%}{m}$;

$$T_{1\gamma_{CO_2}}^{H}(\tau)=T_{v_c}^{H}T_{\gamma_{CO_2}}^{v_c}=15{,}16\cdot e^{-\left(\frac{\tau-3{,}47}{2{,}9}\right)^2}+14{,}21\cdot e^{-\left(\frac{\tau-15{,}57}{2{,}6}\right)^2}+24{,}68\cdot e^{-\left(\frac{\tau-9{,}73}{6{,}0}\right)^2}\ [s];$$

$$T_{2\gamma_{CO_2}}^{H}(\tau)=T_{v_c}^{H}+T_{\gamma_{CO_2}}^{v_c}=7{,}05\cdot e^{-\left(\frac{\tau-3{,}47}{2{,}9}\right)^2}+6{,}61\cdot e^{-\left(\frac{\tau-15{,}57}{2{,}6}\right)^2}+11{,}48\cdot e^{-\left(\frac{\tau-9{,}73}{6{,}0}\right)^2}+2{,}15\ [s].$$

Let represent process (10) as a state-space model in controllable canonical form (11):

$$\begin{cases}\begin{bmatrix}x_1'(t)\\ x_2'(t)\end{bmatrix}=\begin{bmatrix}0, & 1\\ -\dfrac{1}{T_{1\gamma_{CO_2}}^{H}(\tau)}, & -\dfrac{T_{2\gamma_{CO_2}}^{H}(\tau)}{T_{1\gamma_{CO_2}}^{H}(\tau)}\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\end{bmatrix}+\begin{bmatrix}0\\ \dfrac{1}{T_{1\gamma_{CO_2}}^{H}(\tau)}\end{bmatrix}H(t),\\ \gamma_{CO_2}(t)=\begin{bmatrix}k_{\gamma_{CO_2}}^{H} & 0\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\end{bmatrix}.\end{cases} \tag{11}$$

It is known that the metal decarburization rate is also determined by the blast supply rate. At the beginning of the blow, when the carbon mass fraction is high, its oxidation rate varies with the oxygen supply rate to the reaction zone, as decarburization primarily occurs at the interface between the oxygen jet and the molten bath. Towards the end of the blow, when the mass fraction of carbon in the bath reaches a so-called "critical" level, the decarburization rate decreases, as the diffusion of the element being oxidized to the reaction zone becomes the rate-limiting step. In accordance with the concept of two kinetic periods for the carbon oxidation process, the first period is described by equation (12):

$$-\frac{dC}{d\tau}=\frac{K_1\cdot\eta\cdot v}{G_m}, \tag{12}$$

where $\frac{dC}{d\tau}$ – is the bath decarburization rate, $\frac{\%}{min}$; K_1 – is the coefficient characterizing the first kinetic period, $\frac{t\cdot\%}{m^3}$; η – is a coefficient dependent on the volume fraction of oxygen in the blast and its degree of utilization for decarburization; v – is the volumetric flow rate of the oxygen blast, $\frac{m^3}{min}$; G_m – is the mass of the metal bath, t.

In the second kinetic period, which begins when the diffusion fluxes of carbon and oxygen become equal, the decarburization rate is described by equation (13):

$$-\frac{dC}{d\tau}=\frac{\beta SC}{V_m}, \tag{13}$$

Where β – is the carbon mass transfer coefficient in the bath, $\frac{m}{min}$; S – is the surface area where the carbon oxidation process occurs, m^2; C – is the mass fraction of carbon in the bath, %; V_m – is the volume of the metal bath, m^3. The dependency of the average carbon oxidation rate on the specific oxygen consumption rate is depicted in Figure 3.

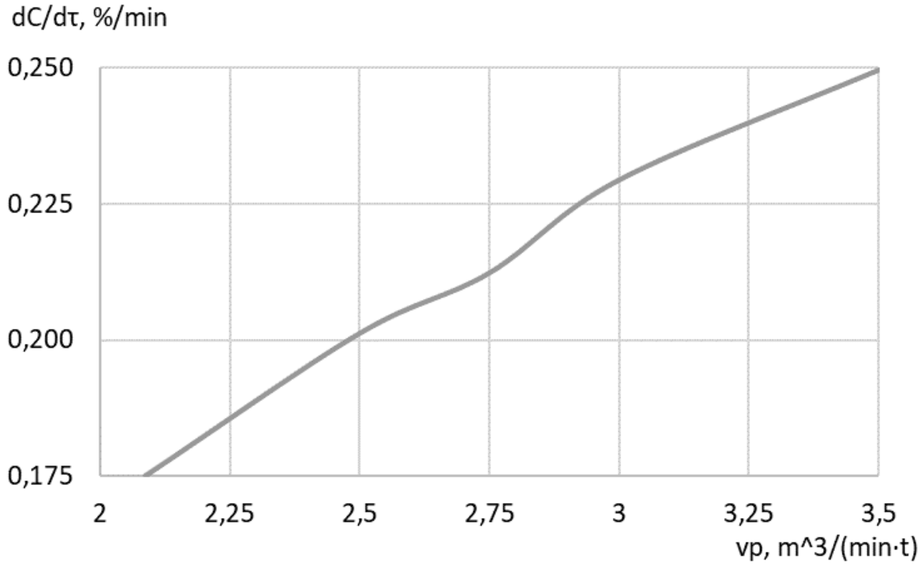

Figure 3: Effect of the blowing intensity on the bath decarburization rate

The transient response of the decarburization rate to changes in the oxygen blast intensity can be described by the following first order differential equation (14):

$$T_{v_c}^{v}\frac{dv_c(t)}{dt}+v_c(t)=k_{v_c}^{v}v(t), \tag{14}$$

where $k_{v_c}^{v}$ – is the process gain for oxygen flow rate to decarburization rate, $\frac{t}{m^3}$; $T_{v_c}^{v}$ – is the time constant, s. The values of the dynamic properties are determined from the studies described above (Figure 1). For a 160-tonne converter, the following values are obtained: $k_{v_c}^{v}=\frac{\Delta v_c}{\Delta v}=\frac{(0{,}367-0{,}322)\frac{t}{min}}{(480-400)\frac{m^3}{mins}}\approx 0{,}56\frac{kg}{m^3}$; $T_{v_c}^{v}\approx 3{,}7\ s$. The transient process for the change in the degree of carbon oxidation to CO_2, resulting from a change in the oxygen blast intensity, is formed by the series connection of (9) and (14) and is described by the differential equation (15):

$$T_{v_c}^{v}T_{\gamma_{CO_2}}^{v_c}\frac{d^2\gamma_{CO_2}(t)}{d^2t}+\left(T_{v_c}^{v}+T_{\gamma_{CO_2}}^{v_c}\right)\frac{d\gamma_{CO_2}(t)}{dt}+\gamma_{CO_2}(t)=k_{\gamma_{CO_2}}^{v}v(t), \tag{15}$$

where $k_{\gamma_{CO_2}}^{v}=k_{v_c}^{v}\cdot k_{\gamma_{CO_2}}^{v_c}=\left(0{,}56\frac{kg}{m^3}\right)\cdot\left(-2{,}25\cdot 10^{-3}\frac{min}{kg}\right)\cdot 100\%=-0{,}126\frac{(\%\cdot min)}{m^3}$.

The process control object for the oxygen blast intensity of an oxygen converter is comprised of the physical connection between a pneumatic valve and a flow meter. This arrangement represents an oxygen capacitance, which creates resistance to fluid flow. This system, with the pneumatic valve position as its input and the oxygen flow rate as its output, is described by the following first-order differential equation (16):

$$T_v^{u_{O_2}} \frac{dv(t)}{dt} + v(t) = k_v^{u_{O_2}} u_{vo_2}(t), \tag{16}$$

where u_{vo_2} – is the pneumatic valve position, %; $k_v^{u_{O_2}}$ – is the process gain for pneumatic valve position to blast intensity, $\frac{m^3}{\%\cdot min}$.; $T_v^{u_{O_2}}$– is the time constant, s. The process gain is $k_v = \frac{\Delta v}{\Delta u_{vo_2}} = \frac{600\frac{m^3}{min}}{100\%} = 6\frac{m^3}{(min\cdot\%)}$. From the handbook [9], the time constant is $T_v^{u_{O_2}}$ =1,2 s.

The transient process for the change in the degree of carbon oxidation to CO_2, resulting from a change in the oxygen pneumatic valve position, is formed by the series connection of (15) and (16) and is described by the differential equation (17):

$$T_{1\gamma_{CO_2}}^{u_{O_2}} \frac{d^3\gamma_{CO_2}(t)}{d^3t} + T_{2\gamma_{CO_2}}^{u_{O_2}} \frac{d^2\gamma_{CO_2}(t)}{d^2t} + T_{3\gamma_{CO_2}}^{u_{O_2}} \frac{d\gamma_{CO_2}(t)}{dt} + \gamma_{CO_2}(t) = k_{\gamma_{CO_2}}^{u_{O_2}} u_{vo_2}(t), \tag{17}$$

where $k_{\gamma_{CO_2}}^{u_{O_2}} = k_{\gamma_{CO_2}}^{v} \cdot k_v^{u_{O_2}} = \left(-0{,}126\frac{(\%_{CO_2}\cdot min)}{m^3}\right)\cdot\left(6\frac{m^3}{\left(min\cdot\%_{u_{O_2}}\right)}\right) = -0{,}756\frac{\%_{CO_2}}{\%_{u_{O_2}}}$; $T_{1\gamma_{CO_2}}^{u_{O_2}} = T_v^{u_{O_2}} T_{v_c}^{v} T_{\gamma_{CO_2}}^{v_c} = 9{,}55\ s$; $T_{2\gamma_{CO_2}}^{u_{O_2}} = T_{v_c}^{v} T_{\gamma_{CO_2}}^{v_c} + T_{v_c}^{v} T_v^{u_{O_2}} + T_v^{u_{O_2}} T_{\gamma_{CO_2}}^{v_c} = 14{,}98\ s$; $T_{3\gamma_{CO_2}}^{u_{O_2}} = T_v^{u_{O_2}} + T_{v_c}^{v} + T_{\gamma_{CO_2}}^{v_c} = 7{,}05\ s$. Let represent process (17) as a state-space model in controllable canonical form (18):

$$\begin{cases} \begin{bmatrix} x_1'(t) \\ x_2'(t) \\ x_3'(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\frac{1}{T_{1\gamma_{CO_2}}^{u_{O_2}}} & -\frac{T_{3\gamma_{CO_2}}^{u_{O_2}}}{T_{1\gamma_{CO_2}}^{u_{O_2}}} & -\frac{T_{2\gamma_{CO_2}}^{u_{O_2}}}{T_{1\gamma_{CO_2}}^{u_{O_2}}} \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_{1\gamma_{CO_2}}^{u_{O_2}}} \end{bmatrix} u_{vo_2}(t), \\ \gamma_{CO_2}(t) = \begin{bmatrix} k_{\gamma_{CO_2}}^{u_{O_2}} & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \end{bmatrix}. \end{cases} \tag{18}$$

A simulation of the purging mode for BOF process was performed in the Matlab Simulink environment (Figure 4, Figure 5, Figure 6). The ode23s (stiff/mod. Rosenbrock) variable-step solver was selected for the simulation. The absolute and relative tolerances for the calculations were set to 0.00001.

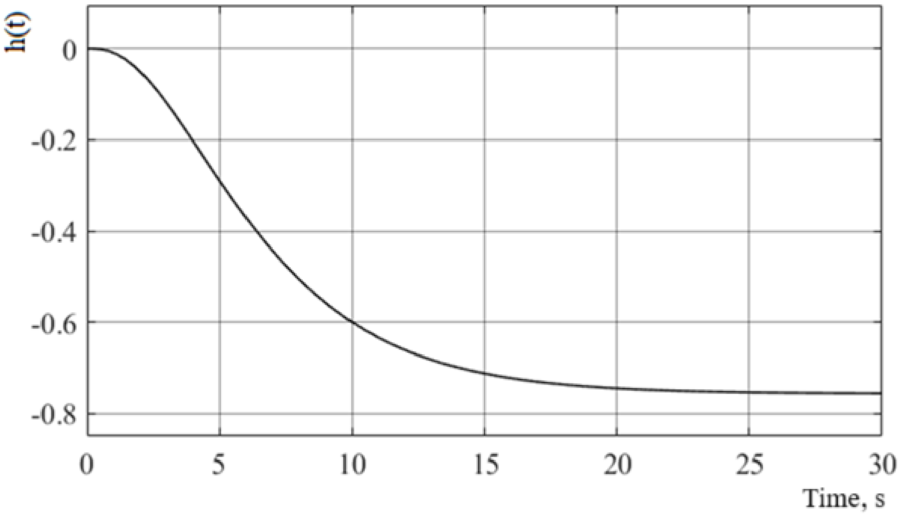

Figure 4: Effect of the blowing intensity on the bath decarburization rate

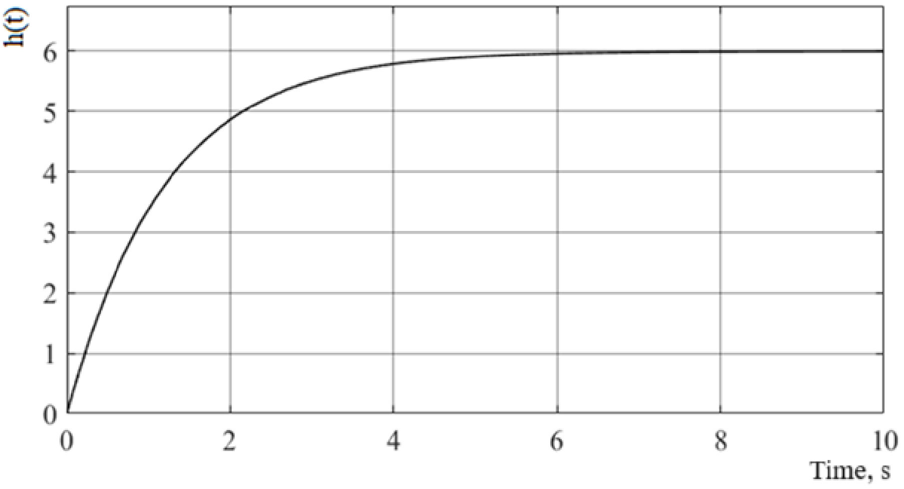

Figure 5: Effect of the blowing intensity on the bath decarburization rate

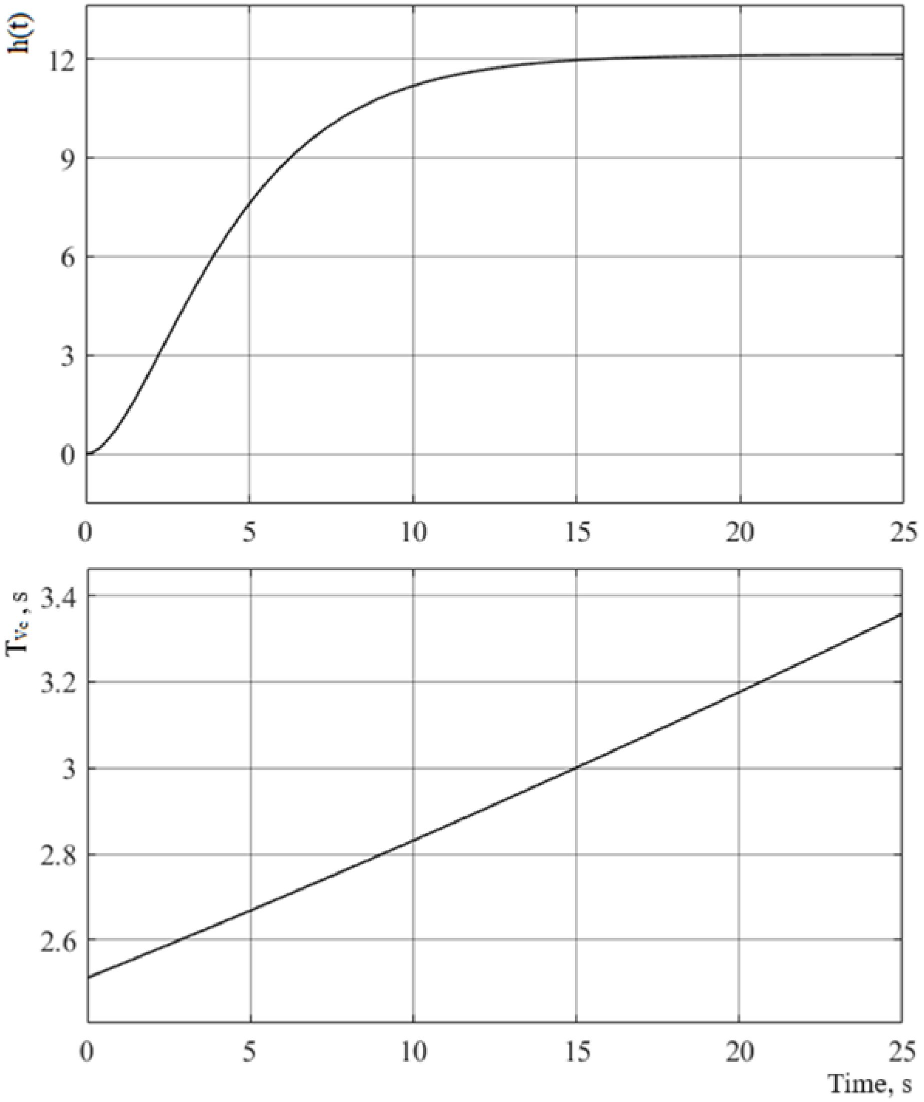

Figure 6: Effect of the blowing intensity on the bath decarburization rate

The resulting model of the purging mode for BOF process, represented in the controllable canonical form of a state-space model (11,18), will subsequently be used for the design of a controller based on the model predictive control approach.

3. Conclusion

The technological features of controlling the parameters of the purging mode for BOF process were analyzed, and a state-space model of this process was developed. It was established that one of the main parameters of the purging mode is the blowing intensity, on which the progress of impurity oxidation and slag formation processes depends. However, increasing the blowing intensity reduces iron oxidation and its transfer into the slag, and also decreases lining wear; this is associated with a reduction in both the blowing duration and the contact time of the refractories with the aggressive slag and high-temperature flame. The effect of the lance height above the quiescent bath level was analyzed. Specifically, increasing the lance height leads to an increase in the basicity and oxidation of the final slag, a higher degree of CO post-combustion in the converter cavity, a decrease in the manganese mass fraction in the metal at the end of the blow, and reduced fluorspar consumption and lining wear. By regulating this distance, the optimal amount of heat generated from the oxidation of CO to CO_2 can be ensured. It was determined that variations in the degree of carbon oxidation to CO_2 within the converter cavity are governed by changes in the decarburization rate, which, in turn, is governed by the lance height above the quiescent bath level. The process of the decarburization rate changing in response to a change in lance height is non-stationary and is described by a first-order differential equation whose time constant depends on the stage of the blow. The effect of blast supply intensity on the metal decarburization rate was investigated. The transient process for the change in the degree of carbon oxidation to CO_2, resulting from a change in the oxygen pneumatic valve position, is described by a third-order differential equation. A prediction model of the purging model for the oxygen converter process was obtained in the controllable canonical form of a state-space model, dependent on changes in the lance height above the quiescent bath level and the blast intensity. This model was used as the predictive model for the control system. The numerical values of the dynamic properties of the resulting model are provided.

Declaration on Generative AI

During the preparation of this work, the authors used Gemini 2.5 and DeepL for translation, grammar, and spelling checks. After using these services, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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