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Numerical simulation for the thermal regime of slag-splashing lance during hot repair of BOF lining

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Computer modelling is increasingly essential for advancing the practice of the most widespread and efficient basic oxygen furnace (BOF) steelmaking process. An urgent problem in the BOF process is the need for greater durability of the refractory lining in the top-blown converter. One of the most advanced methods of hot repair for the converter lining is the inter-melting slagging technology for refractories, with a durable skull coating. An essential task in implementing the progressive slag-splashing process is ensuring proper and stable durability of the slag-splashing lances used. A mathematical model of the thermal regime of the top water-cooled slag-splashing lance barrel during the hot repair operation of the converter lining by the slag-splashing method has been developed. The regularities of heat transfer and temperature changes in the outer pipe of the slag-splashing lance for two primary forms of blast devices, operated under technological conditions of lining slagging in top-blown converters with typical capacities of 160 tonnes and 250 tonnes, are numerically investigated. Regression dependencies for estimating the thermal regime of the slag-splashing lance barrel at different cooling water flow rates have been obtained. The results obtained are used to design a slag-splashing lance and to develop its operating technology during hot repair of the lining of a 250-tonne top-blown converter with the use of the slagging method. The results contribute to the development and improvement of automated design systems, the modernisation of slag-splashing lances, and the control of BOF steelmaking. They also contribute to the development and improvement of automated design and modernisation systems, as well as to the solution of optimisation and predictive analysis problems for the thermal regime of slag-splashing lances in the context of BOF steelmaking control.

Keywords: BOF, slag-splashing process, slag-splashing lance, lance durability, thermal regime, numerical simulation

INTRODUCTION

International and European initiatives, such as the UN 2030 Sustainable Development Goals, the Paris Agreement, and the European Green Deal, aim to increase the sustainability of industrial production and reduce CO_2 emissions. CO_2 emissions are most critical in the steel industry, and their reduction is only possible with process optimisation and the development of new energy- and resource-saving technologies and production methods. High temperatures and aggressive environments inside metallurgical units make it impossible to directly measure the parameters required to analyse and optimise metallurgical processes. In metallurgical production, exhaust gas analysis and spot measurements with subsequent sample analysis are often the primary sources of information. More modern, direct, and continuous measurement methods for many processes remain unavailable. In addition, laboratory and industrial studies to evaluate optimisation strategies are costly and unsafe. Thus, modelling and simulation are the only alternative low-cost, safe, and effective sources of information on unknown parameters of metallurgical processes. In addition, computer models can be used for model-based control of metallurgical processes [1].

Computer modelling is also becoming increasingly important in the practice of the BOF process, the most widespread and efficient method of steelmaking. This is especially evident against the background of growing computing power and the development of technologies and tools that enable the execution of labour-intensive tasks in numerical modelling, extensive data control, high-precision calculations, etc. Modern virtual models of complex technological processes and systems can significantly reduce material and time costs for their study, optimisation, and further automation. The task of fundamentally generalised modelling of the BOF process is ultimately set to enable accurate process control based on real-time data. Understanding the process based on knowledge gained from modelling is an essential component of implementing intelligent production – a modern strategy for developing the steel industry [2–4]. Smart process control systems, including various real-time recognition and forecasting subsystems based on computer vision, are increasingly used to control the BOF process [5].

LITERATURE REVIEW

The efficiency of modern steelmaking, associated [6] with reduced energy consumption, improved final product quality, and increased product output, is determined by the degree of automation and control of the BOF process. To solve these problems, it is essential to develop and improve traditional physical and chemical models that account for the main physical and chemical processes occurring during smelting, as well as modern hybrid systems, including computer modelling, machine learning methods, and neural networks [7–10].

A topical issue of the BOF process remains the insufficient durability of the top-blown converter refractory lining [11]. One of the progressive methods for the hot repair of the converter lining is the inter-melting slagging technology for refractories with a durable skull coating [12]. In this case, slag from the previous smelting is left in the converter, with the addition of special magnesia fluxes, followed by blowing the prepared slag with nitrogen or nitrogen-powder jets onto the worn lining of the unit walls [13].

The following cycle of modern works is devoted to modelling processes and to studying problems associated with slag splashing during the hot repair of the converter lining.

The influence of various factors on the efficacy of the slag-splashing process was studied in [14]. These factors included the physical and chemical properties of slag, such as basicity, surface tension, and viscosity. Process parameters, such as lance height, the movement of nitrogen, and flow rate, were also considered. Additionally, geometric characteristics of the converter and lance were examined, including the number of lance holes and their angle. This study utilised physical cold and thermodynamic simulation to analyse the impact of these factors on the process efficiency. Studies conducted on a physical cold model at a scale of 1:10 340-t of a top-blown converter from Ternium Brasil Company (in Rio de Janeiro) showed that the intensity of slag splashing depends on its viscosity and the fraction of solid particles. Thermodynamic modelling enabled estimation of the phases of viscosity change in the slag during its interaction with an injected nitrogen jet.

In [15, 16], the influence of technological factors on the slag-splashing process in top-blown converters is analysed using physical and mathematical modelling. In [15], the use of three-dimensional mathematical modelling to investigate the slag-splashing process in a 120-t top-blown converter is described. It was found [15, 16] that high efficiency of the slag-splashing process is achieved through the optimisation of numerous technological parameters of the blast, including pressure, flow rate and temperature of nitrogen, height, and angle of the lance, slag level, and MgO consumption. The chemical and mineralogical composition of the slag, along with its physical and chemical parameters, is also essential [16]. The modelling results [15] show that, with an increase in the volume of the remaining slag, the density and splash area increase, with the latter having the most significant effect on the process. As the lance height decreases, these parameters first increase and then decrease. The splash area is directly proportional to nitrogen consumption. At a higher lance position, its effect on the sputtering density is minimal, but at a low lance position, the sputtering density increases with increasing nitrogen flow rate. The results of numerical modelling agree with those of laboratory experiments and are used to predict the optimal operating parameter range.

In [17], laboratory and numerical studies of the slag-splashing process are presented using a special gas-cooled (instead of water-cooled) lance of a simplified design for blowing slag with supersonic jets in the converter. The maximum nitrogen heating temperature in the lance reached 493°C. The results showed that gas cooling of the lance promotes heat recovery, increasing thetemperature of the injected mixture and kinetic energy of the jet by about 3.5 times. This enables improved efficiency of the slag-splashing process compared to using a water-cooled lance.

A mathematical model was developed [18] to describe nitrogen and slag flows under transient and isothermal conditions, to extend the service life of the refractory lining in top-blown converters during the slag-splashing process. The model was used to study the influence of various slag parameters, such as temperature, density, viscosity and inter-phase tension, on the durability of refractories.

In [19, 20], an innovative approach to the slag-splashing process using CO_2 (instead of N_2) for slag blowing was studied using numerical simulation, including [19] using a nozzle-twisted lance. The studies show that using CO_2 instead of N_2 decreases the jet velocity and the slag mass flow rate across various areas. However, an innovative nozzle-twisted lance delivers higher radial and tangential velocities and a larger impact area than a traditional lance. In addition, excellent molten pool mixing ability increased the average slag velocity and decreased the dead zone size. This enabled the amalgamation of carbon powder and the interphase reaction between CO_2 and slag. Furthermore, the addition of bottom blowing compensated for the existing shortcomings by increasing the slag mass flow rate and thereby enhancing its mixing. The study confirms the feasibility and potential of the proposed technology to reduce industrial CO_2 emissions.

In [21], a slagging method was developed to calculate the complex radiation-convective heat transfer at the top of the water-cooled slag-splashing lance barrel during hot repair of the converter lining. The complex heat exchange was calculated based on the additivity principle. As a result of the calculations, it was found that during the hot repair of the converter lining, the slag-splashing lance barrel operates under complex thermal conditions. The study provides calculated values of the heat flux density at the outer surface of the barrel due to heat exchange with the exhaust gases. The work also presents calculated heat flux densities characterising heat transfer between the inner surface of the barrel and the cooling water. In addition, the calculated values of the incident radiation flux on the outer surface of the lance barrel are presented in the study. With an increase in the exhaust gas velocity within the considered range, the heat flux density to the lance barrel grows significantly. The results obtained are utilised in the design of water-cooled blast lances and in the optimisation of their operation.

The examination of the current state of the problem revealed a shift in the methods used to study metallurgical processes and systems toward computer modelling. This is undoubtedly due to the rapid development of computing tools, computer technologies, and programming tools that ensure the implementation of labour-intensive tasks such as modelling and managing big data, high-precision calculations, etc. Automation, process control, and forecasting, based on mathematical modelling and simulation, are priority tasks in the modern steel industry.

The publications in the field of numerical research on the slag-splashing process showed a complete lack of popular mathematical and computational models of the thermal regime of slag-splashing lances, thereby hindering the implementation of advanced technology for hot repair of the converter lining. At present, the known works are devoted to computer modelling [22] and the development of an information-modelling system for predicting [23] the thermal regime of the top oxygen lance. However, there is no information on similar studies regarding slag-splashing lances, which confirms the significance of this research and the novelty of its findings.

In this regard, the following tasks are set in the work:

- develop a mathematical model of the thermal regime of the top water-cooled slag-splashing lance (hereinafter referred to as slag-splashing lance) barrel for the technological period of hot repair of the converter lining by the slagging method;
- develop an algorithm for implementing the mathematical model of the slag-splashing lance barrel's thermal regime on a computer, including parallel computing with a modern multiprocessor architecture;
- numerically study the patterns of heat transfer and temperature changes in the outer pipe of the slag-splashing lance;
- use the obtained modelling results to develop an industrial slag-splashing lance that ensures high-performance characteristics and improved technical and economic indicators of hot repair of the converter lining.

The solution to the problems set will ensure the practical design of new and modernised lance designs, improve the cooling system, predict and signal overheating, and ensure the lance remains in an emergency condition throughout its service life. This will ultimately increase the durability of the lance and prevent accidents in production.

RESEARCH METHODOLOGY

The object of the study is complex heat-exchange processes in the slag-splashing lance during hot repair of the converter lining. The study focuses on the thermal regime of the blast device barrel during the slag-splashing process.

The mathematical model of the thermal regime of the slag-splashing lance barrel is based on the heat-conduction differential equation, which relates the temporal and spatial changes in the wall temperature of the out pipe of the device, and is supplemented by boundary conditions (unambiguous conditions).

In this work, a conservative difference scheme for the heat conduction equation is obtained by the integral-interpolation method (balance method), i.e., by directly approximating the heat balance relations for elementary volumes. In this instance, expressions are employed to model heat flows at the boundaries of the computational domain, thereby ensuring compliance with the specified matching conditions. [24–26].

To solve the problem, an implicit difference scheme was used, ensuring absolute stability for any time step, selected solely to achieve the required calculation error.

When writing the resulting system of heat balance equations in canonical form:

$$\begin{gathered} a_i x_{i-1} - c_i x_i + b_i x_{i+1} = -f_i, \\ a_i \neq 0,\ b_i \neq 0,\ 1 \leq i \leq n \end{gathered} \tag{1}$$

where $a_1 = b_n = 0$, the boundary value problem (1) is a system of n linear algebraic equations with a tridiagonal matrix. This type of matrix allows calculations to be organised using a modified Gauss method (tridiagonal matrix algorithm – TDMA) [24–26].

A combination of left and right TDMAs provides a counter TDMA, which allows parallelising the algorithm into two computational flows for further implementation on modern multiprocessor computers [27].

The heat conduction problem considered in this paper is nonlinear (quasilinear). Here, the tabular thermophysical quantities of the heat conduction equation and the heat transfer coefficients in the boundary conditions are approximated by functions of the unknown temperature calculated at the previous time step. In this case, heat-conductivity coefficients in the expressions for the grid analogues of heat flows are replaced by the so-called effective thermal conductivity of segments.

When considering the boundary conditions of the problem (1), it is more expedient to present the initial heat transfer equations and their solutions in the criteria form and to calculate the radiation component of heat exchange using the zonal method [24].

The mathematical description of the model presented uses the authors' calculation technique [21] for complex radiation-convective heat exchange of the slag-splashing lance barrel.

Slag-splashing lances cooled by compressed nitrogen are not considered in this paper.

When developing the mathematical model, the following scheme for hot repair of the converter lining slag belt and the operating conditions of the slag-splashing lance during the specified period of the technological process were used, as described in detail, for example, in [13, 21].

The final slag with the required skull properties is given in the unit bath during the steelmaking process. After the melt is tapped and the slag is cut off, the slag-splashing lance is introduced into the converter cavity and used to blow the slag with nitrogen or nitrogen-powder jets. The slag freezes onto the worn lining, forming a stable skull layer. In this case, both standard oxygen and auxiliary slag-splashing lances, including those with a two-level nozzle arrangement, can be used.

The disadvantage of using standard oxygen lances for slag blowing is the limited ability to ensure proper durability of the lining skull coating and to promptly adjust and restore the converter working space profile. At the same time, special slag-splashing lances ensure the formation of slag droplets with the required properties directly in the zone of interaction between the gas jets and the slag, remove slag droplets from the outgoing gas-slag flow, and freeze the necessary thickness of the skull layer on the unit walls. Two-level slag-splashing lances also reduce the chaotic removal of slag droplets, ensuring they are directed to specific, more worn zones of the converter lining (Fig. 1).

Regardless of the design, the slag-splashing lances are an axisymmetric system of coaxially located pipes (Fig. 2), through which nitrogen and/or a nitrogen-powder mixture are supplied to the unit cavity. The design is water-cooled, with water discharged through the external circuit of the system.

Water is supplied to the lance from the workshop main under pressure up to 0.1 MPa. It is assumed that the size of the annular gap between the external and separating pipes along the lance length is the same, and water pressure losses can be neglected here.

It is assumed that the outer surface of the lance barrel is oxidised and free of wear, accretions, or other heat-insulating coatings during the entire lining repair operation.

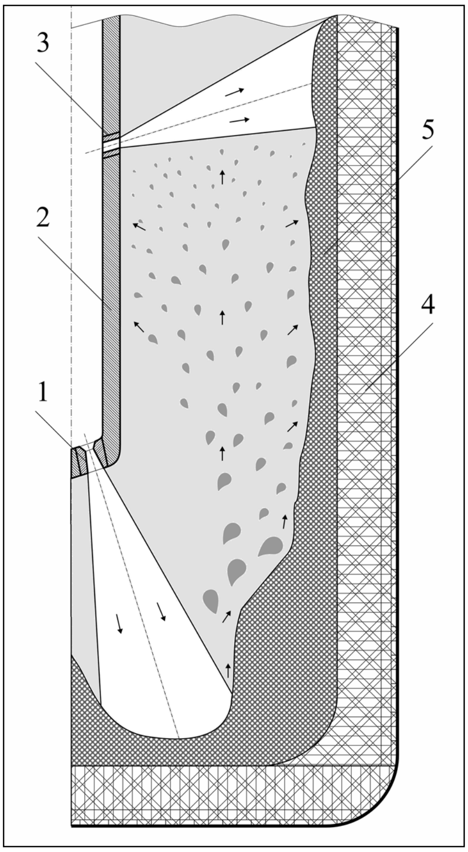

Fig. 1. Scheme of hot repair of the converter lining using two-level slag-splashing lance: 1 – Laval nozzles; 2 – barrel of the slag-splashing lance; 3 – cylindrical nozzles of the second level; 4 – lining; 5 – scull layer

The lance is in a diathermic (transparent) environment and is held at a constant height above the blown slag in a still state.

Compressed nitrogen gas and/or gas-powder jets entering the top-blown converter cavity and heating it to the temperature of the working space expand in accordance with the Gay–Lussac law and leave the unit through the neck.

The temperatures of the working space (i.e., slag), the working surface of the lining, and the gases leaving the converter are assumed to be constant and uniform throughout the entire hot lining repair operation.

Thus, throughout the duration of the entire operation of hot repair of the converter lining by the slag-splashing technology, a complex radiation-convective heat exchange with moving flows of cooling water, exhaust gases, and heat-radiating surfaces of the unit wall lining and slag takes place on the working (located in the converter cavity) surface of the slag-splashing lance.

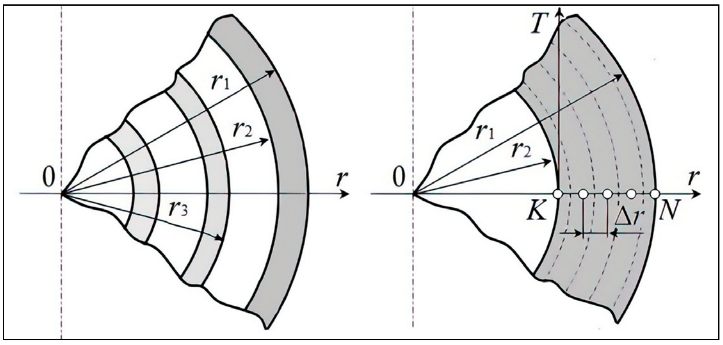

Fig. 2. Horizontal section of the slag-splashing lance and cylindrical approximation of the computational domain

The heat-exchange conditions are assumed identical along the entire external working surface of the lance barrel, given the insignificant water heating in the considered section, allowing us to apply a one-dimensional cylindrical approximation to the calculation domain (Fig. 2).

Thus, taking into account the above conditions, the temperature field of the outer lance pipe is described by the boundary value problem of heat conductivity in cylindrical coordinates ($r_2 \le r \le r_1$):

$$c\rho \frac{\partial T}{\partial \tau} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda \frac{\partial T}{\partial r} \right), \tau > 0, \qquad (2)$$

$$-\lambda \frac{\partial T}{\partial r}\bigg|_{r=r_2} = \alpha_2 (T_{\text{int}} - T_{\text{H}_2\text{O}}), \qquad (3.1)$$

$$-\lambda \frac{\partial T}{\partial r}\bigg|_{r=r_1} = \alpha_1 (T_{ext} - T_{eg}) + q_r, \qquad (3.2)$$

$$T(r, 0) = T_0, \qquad (4)$$

where c is the specific heat capacity, J/(kg·K); ρ is the density, kg/m^3; λ is the thermal conductivity, W/(m·K); T, T_{int}, T_{ext}, T_{H2O}, T_{eg}, T_0 are the computed temperature, the temperature of the internal surface of lance barrel, the temperature of the external surface of lance barrel, the temperature of the water in the outer cooling circuit, the temperature of the exhaust gases, and the initial temperature of the lance, respectively (all in K); τ is the process time, s; α_1, α_2 are the heat transfer coefficients from the outer pipe to exhaust gas and to the water, respectively (all in W/(m^2·K)); q_r is the flux density of the resulting radiation for the outer surface, W/m^2, calculated here based on the zonal method [21, 28].

A system of three linear algebraic equations for three unknown effective radiation fluxes of the surfaces participating in heat exchange (lance barrel, converter lining working space, slag mirror) was solved by the Newton–Raphson method. Ultimately, calculating the resultant radiation at the outer surface of the lance barrel, q_r [21] requires the determination of angular radiation coefficients of the specified system of surfaces [29, 30].

Further, when the calculated value is directly recorded in the implicit finite-difference approximation of equation (3.2), problems arise in its implementation by the TDMA when the temperature near the target coefficients must be reduced to the first degree. To avoid this, it is advisable to use the so-called coefficient of radiation heat exchange [21, 24–26]:

$$\alpha_r = q_r/\Delta T, \qquad (5)$$

where $\Delta T = |T_{ext} - T_{eg}|$ is the calculated temperature head between the temperature of the outer wall and the temperature of the converter working space (the temperature of the exhaust gases), K.

Now, for the boundary value problem (2)–(4), taking into account (5), an implicit difference scheme constructed by the integral-interpolation method can be formulated [24]:

$$\begin{aligned} &(K+1/4)\frac{c_K\,\rho_K\,\Delta r}{2\Delta\tau}\left(T_K^{\tau+\Delta\tau} - T_K^{\tau}\right) = \\ &= K\,\alpha_2\left(T_{\text{H}_2\text{O}} - T_K^{\tau+\Delta\tau}\right) - \\ &-(K+1/2)\frac{\lambda_{K+1/2}}{\Delta r}\left(T_K^{\tau+\Delta\tau} - T_{K+1}^{\tau+\Delta\tau}\right), \end{aligned} \qquad (6)$$

$$\begin{gathered}
i\frac{c_i\,\rho_i\,\Delta r}{\Delta\tau}\left(T_i^{\tau+\Delta\tau}-T_i^{\tau}\right)=\\
=\left(i-1/2\right)\frac{\lambda_{i-1/2}}{\Delta r}\left(T_{i-1}^{\tau+\Delta\tau}-T_i^{\tau+\Delta\tau}\right)-\\
-\left(i+1/2\right)\frac{\lambda_{i+1/2}}{\Delta r}\left(T_i^{\tau+\Delta\tau}-T_{i+1}^{\tau+\Delta\tau}\right), K<i<N,
\end{gathered} \qquad (7)$$

$$\begin{gathered}
\left(N-1/4\right)\frac{c_N\,\rho_N\,\Delta r}{2\Delta\tau}\left(T_N^{\tau+\Delta\tau}-T_N^{\tau}\right)=\\
=\left(N-1/2\right)\frac{\lambda_{N-1/2}}{\Delta r}\left(T_{N-1}^{\tau+\Delta\tau}-T_N^{\tau+\Delta\tau}\right)-\\
-N\left[\left(\alpha_1+\alpha_r\right)\left(T_N^{\tau+\Delta\tau}-T_{eg}\right)\right],
\end{gathered} \qquad (8)$$

where $\Delta\tau$ is the time step, s; $\lambda_{i\pm1/2}$ is the effective thermal conductivity coefficient of the segments, calculated by the formula

$$\lambda_{i\pm1/2}=2\frac{\lambda\left(T_i^{\tau}\right)\cdot\lambda\left(T_{i\pm1}^{\tau}\right)}{\lambda\left(T_i^{\tau}\right)+\lambda\left(T_{i\pm1}^{\tau}\right)} \qquad (9)$$

Thermophysical quantities c, λ, ρ in (6)–(9) are obtained as a result of approximation by temperature functions of the corresponding tabular values for pipe steel.

Due to the limited possibilities and complexity of the analytical or numerical solution of the associated heat transfer problems, the heat transfer equations in the flows under study are presented in criteria form [21]:

$$\mathrm{Nu}=\alpha_f d_e/\lambda_f$$

where α_f, λ_f are, respectively, the heat transfer coefficient and thermal conductivity of the cooling water flow in (6) or the exhaust gas in (9) in the considered channel with an equivalent diameter of d_e, m.

As the rough calculation showed, within the given range of water and nitrogen flow rate variation in the studied channels of the computational domain, the coolant flow is in a developed turbulent regime (Reynolds number Re ≥ 10^4). The required interpolation formula for calculating forced convection on the corresponding surface of the annular channel can be selected, for example, from [21, 31].

The water temperature in the outer contour of the lance is taken as average in the heat exchange section $0 \le x \le l$, calculated by the Newton–Richmann law [31]:

$$\begin{gathered}
\frac{dT_{\mathrm{H_2O}}\left(x\right)}{dx}=\frac{4}{\left(d_2^2-d_3^2\right)\rho_{\mathrm{H_2O}}\,c_{\mathrm{H_2O}}w_{\mathrm{H_2O}}}\times\\
\times\left[\alpha_3\,d_3\left(T_0-T_{\mathrm{H_2O}}\left(x\right)\right)+\right.\\
\left.+\alpha_2\,d_2\left(T_K-T_{\mathrm{H_2O}}\left(x\right)\right)\right],
\end{gathered} \qquad (10)$$

where $w_{\mathrm{H_2O}}$ is the water flow rate in the outer contour of the lance, m/s; $\rho_{\mathrm{H_2O}}$ is the density of water, kg/m^3; $c_{\mathrm{H_2O}}$ is the specific heat capacity of water, J/(kg·K); α_3 is the heat transfer coefficient from the inner pipe to water, W/(m^2·K)**;** l is the length of the working part (inside the converter) of the lance, m.

According to the calculations in [21], $\alpha_2/\alpha_3 \approx 0.98$–$0.99$, therefore, equation (10) can be reduced to a simplified form:

$$\begin{gathered}
\frac{dT_{\mathrm{H_2O}}\left(x\right)}{dx}=\frac{4\mathrm{St}}{d_2^2-d_3^2}\left[d_3\left(T_0-T_{\mathrm{H_2O}}\left(x\right)\right)+\right.\\
\left.+d_2\left(T_K-T_{\mathrm{H_2O}}\left(x\right)\right)\right],
\end{gathered}$$

where $\mathrm{St}=\dfrac{4\alpha_2}{\rho_{\mathrm{H_2O}}\,c_{\mathrm{H_2O}}w_{\mathrm{H_2O}}}$ is the Stanton number.

The calculation technique for the heat transfer coefficients and radiation heat exchange is described in [21].

RESULTS AND DISCUSSION

For a numerical solution by TDMA [24–26], the resulting system of heat balance equations is presented in the form (1), where $x = T$, $K \le i \le N$, and the coefficients of the tridiagonal finite-difference scheme are computed using the following formulas:

$$a_i=a\cdot\left(i-1/2\right)\frac{\sigma_i\lambda_{i-1/2}}{\Delta r^2}, \qquad (11)$$

$$b_i=b\cdot\left(i+1/2\right)\frac{\sigma_i\lambda_{i+1/2}}{\Delta r^2}, \qquad (12)$$

$$\begin{gathered}
c_i=1+a_i+b_i+i\frac{\sigma_i}{\Delta r}\left[\left(1-a\right)\cdot\alpha_2+\right.\\
\left.+\left(1-b\right)\cdot\left(\alpha_1+\alpha_r\right)\right],
\end{gathered} \qquad (13)$$

$$\begin{gathered}
f_i=T_i^{\tau}+i\frac{\sigma_i}{\Delta r}\left[\left(1-a\right)\cdot\alpha_2 T_{\mathrm{H_2O}}+\right.\\
\left.+\left(1-b\right)\cdot\left(\alpha_1+\alpha_r\right)T_{eg}\right],
\end{gathered} \qquad (14)$$

where $\sigma_i=\dfrac{2}{a\cdot\left(i-1/4\right)+b\cdot\left(i+1/4\right)}\cdot\dfrac{\Delta\tau}{\rho_i c_i}$

In (11)–(14), depending on the position of the node on the computational grid [24–26]:

– $a = 0$, $b = 1$ for $i = K$;

– $a = 1$, $b = 1$ for $K < i < N$;

– $a = 1$, $b = 0$ for $i = N$.

Numerical modelling of the thermal regime of the slag-splashing lance barrel is performed for two main form factors of blast devices, operated under the technological conditions of hot repair of the converter lining, with typical capacities of 160 tonnes and 250 tonnes, respectively (Table 1).

Table 1. **Initial data for numerical modelling**

Parameter, m (Fig. 2)	Top-blown converter capacity	
	160 tonnes	250 tonnes
d_1	0.219	0.426
d_2	0.203	0.408
d_3	0.168	0.325

Similar production capacities are characteristic of the Ukrainian metallurgical industry.

The working length of the lance located in the converter cavity is 6.7 m and 9.0 m, respectively, and the lance height above the slag level in a still state is, on average, 0.5 m. The calculated diameters of the cylinders approximating the working space of the converter when solving the problem of complex radiation-convective heat exchange of the lance barrel during the process of slag blowing are 4.7 m and 5.7 m, respectively.

The nitrogen consumption for slag blowing is 400 m^3/min and 600 m^3/min, respectively, ensuring a gas velocity of approximately 7 m/s leaving the converter, regardless of the unit load.

During the modelling, the velocity of the cooling water along the outer contour of the lance was varied from 1 to 10 m/s.

The temperature of the working space, i.e. slag, working surface of the lining, and gases leaving the converter are assumed, as indicated earlier, to be constant and the same during the entire hot repair operation of the lining, and equal to 1600°C.

The computer implementation of the developed mathematical model was performed in Microsoft Visual Studio C++ 2022 IDE.

As a result of computer modelling, it was found that the convective component of the complex radiation-convective heat exchange on the outer surface of the lance barrel is negligibly small compared to its radiation component. At the working gas flow rate for blowing slag (~7 m/s) and the temperature of the outer surface of the barrel (~150°C), its value does not exceed 1.6–1.9% of the total heat input in the considered section of the lance, depending on the unit charge.

In the numerical modelling process, a stationary (steady-state) temperature field of the slag-splashing lance barrel was obtained at different cooling water flow rates for the lining slagging operation of 160 tonnes (Fig. 3) and 250 tonnes (Fig. 4) top-blown converters, respectively.

With a working water flow rate of 100 m^3/h and 300 m^3/h for a top-blown converter capacity of 160 tonnes and 250 tonnes, respectively, the calculated temperature of the inner surface of the lance barrel is 75–105°C, and the outer surface is 150–190°C (Figs 3, 4).

Obviously, with a given inlet water temperature, an increase in the water velocity in the outer annular channel of the device improves the cooling of the lance and, therefore, increases its durability. This can be ensured by increasing the water flow rate or reducing the flow area of the specified water-cooling circuit.

The best approximation of the calculated data (Fig. 5) is ensured by their approximation by the following regression functions:

– for a 160-t top-blown converter

$$\begin{cases} T_K = 1.23 \cdot 10^4 \exp\left(-4.5 w_{\mathrm{H_2O}}^{0.1}\right) - 6.9, \\ T_N = 1.26 \cdot 10^4 \exp\left(-4.5 w_{\mathrm{H_2O}}^{0.1}\right) + 64.1; \end{cases}$$

– for a 250-t top-blown converter

$$\begin{cases} T_K = 1.30 \cdot 10^4 \exp\left(-4.5 w_{\mathrm{H_2O}}^{0.1}\right) - 8.9, \\ T_N = 1.33 \cdot 10^4 \exp\left(-4.5 w_{\mathrm{H_2O}}^{0.1}\right) + 72.2, \end{cases}$$

calculations for which, with a working water flow rate of 100 m^3/h and 300 m^3/h, respectively, showed the following temperature values:

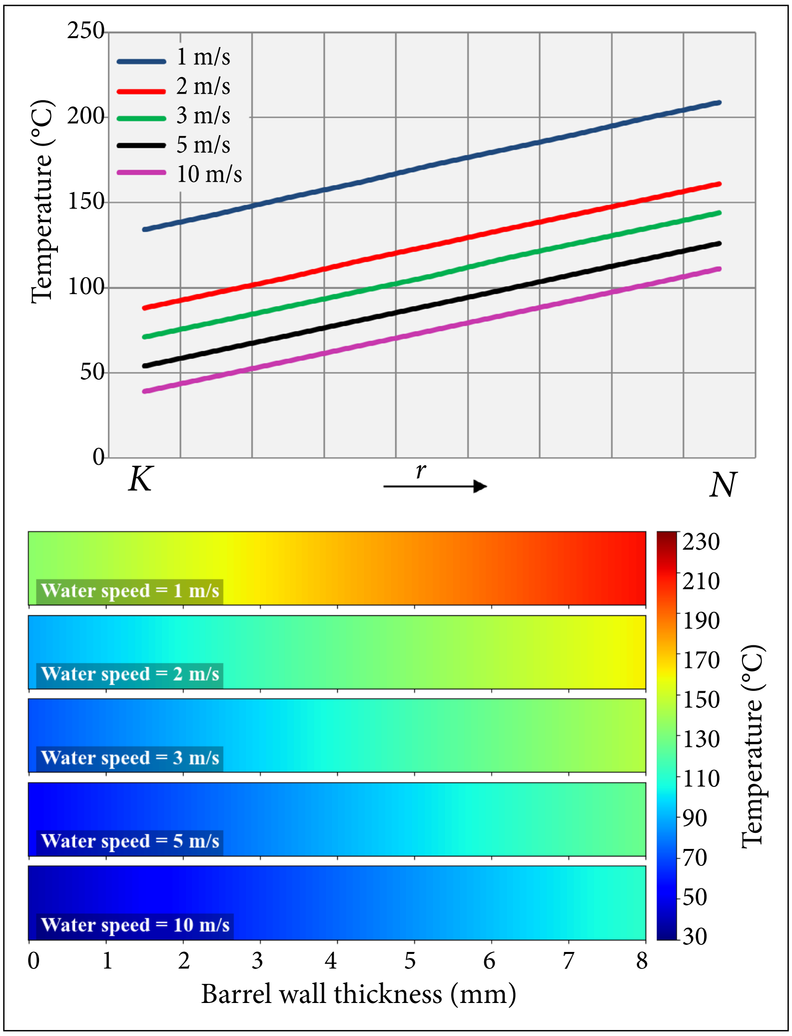

Fig. 3. Distribution of temperatures of the slag-splashing lance barrel at different water speeds in the external cooling circuit of the device during slag blowing in 160-t top-blown converters

– for 160-t top-blown converter: T_K = 78°C, T_N = 151°C;

– for 250-t top-blown converter: T_K = 103°C, T_N = 186°C.

The obtained dependencies correspond with the results of computer modelling [22] used in the previously developed information-modelling system for predicting the thermal regime of the top converter lance barrel [23].

Based on computer modelling results, a new slag-splashing lance was designed and tested in a 250-t top-blown converter at KAMET–STAL JSC (METINVEST). The lance tip has two primary (nozzle with a critical diameter d_{cr} = 43 mm, nozzle exit diameter d_{ex} = 49 mm, located at angle α = 17°), and four additional (d_{cr} = 37 mm, d_{ex} = 43 mm, α = 17°) Laval nozzles. The main nozzles are located in the trunnion plane, the most-worn part of the converter lining. Nitrogen consumption for slag blowing is 600-700 m^3/min. A detailed description of the slag-splashing lance design and the technology of hot repair of the converter lining using it is presented in [32].

Using the developed lance design for hot repair of the lining ensured rapid restoration of the rational profile of the converter lining in a short time with the formation of a durable skull slag coating. At the same time, violations of lance durability, such as barrel deformations or cracks in external welds, water leaks, and other

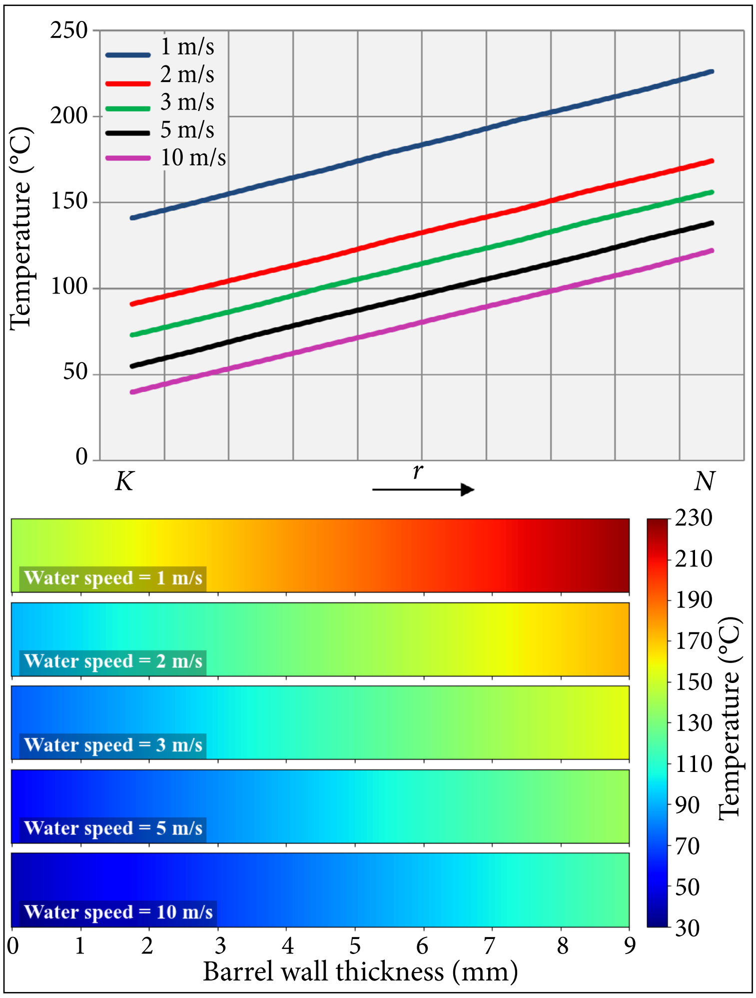

Fig. 4. Distribution of temperatures of the slag-splashing lance barrel at different water speeds in the external cooling circuit of the device during slag blowing in 250-t top-blown converters

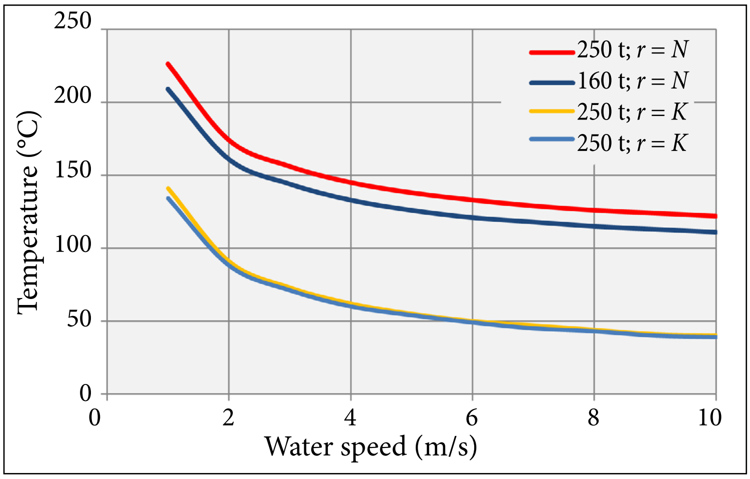

Fig. 5. Effect of cooling water velocity in the outer circuit on the temperature of the inner and outer surface of the slag-splashing lance throughout the duration of slag blowing in 160-t and 250-t top-blown converters

emergencies, were not observed during the experimental industrial campaign. An increase in converter productivity was achieved through reduced downtime for hot lining repairs, increased refractory durability, and lower refractory material consumption during lining repairs.

CONCLUSIONS

A mathematical model of the thermal regime of the slag-splashing lance barrel during the hot repair operation of the top-blown converter lining by the slag-splashing technology has been developed.

The proposed mathematical description represents a boundary-value quasi-linear heat-conduction problem. The conservative implicit difference scheme is obtained by the integral-interpolation method in cylindrical coordinates. The TDMA solves the system of heat balance equations.

When considering the boundary conditions of the problem, the initial heat transfer equations and their solutions are presented in the criteria form, and the radiation component of heat exchange is calculated employing the zonal method.

An algorithm and a program for the computer implementation of the presented mathematical model in the Microsoft Visual Studio C++ 2022 IDE have been developed, including for high-performance parallel computing on a modern multiprocessor computer architecture.

The regularities of heat transfer and temperature changes in the outer pipe of the slag-splashing lance are numerically investigated for two primary forms of blast devices, operated under technological conditions for hot repair of the lining of top-blown converters with typical capacities of 160 tonnes and 250 tonnes. Regression dependencies are obtained that allow estimating the thermal regime of the barrel of the blowing lance of converters of typical capacities at different flow rates of cooling water.

The obtained results were used to design the skull lance and to develop and optimise the technology for its operation during hot repair of the lining of a 250-t top-blown converter using the slag-splashing method.

Based on the presented computer model, an information-modelling system for predicting the durability of top blast lances is planned. This system would facilitate the development and improvement of automated design systems, the modernisation, and the predictive analysis of the thermal regimes of slag-splashing lances for BOF steelmaking control [33, 34].

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References

1. Echterhof T., Ohno K.-I., Visuri V.-V. Modeling and simulation of metallurgical processes in ironmaking and steelmaking. *Metals*. 2022. Vol. 12. No. 7. 1185. https://doi.org/10.3390/met12071185
2. Cao L., Wang Y., Liu Q., Feng X. Physical and mathematical modeling of multiphase flows in a converter. *ISIJ International*. 2018. Vol. 58. No. 4 P. 573–584. https://doi.org/10.2355/isijinternational.ISIJINT-2017-680
3. Shanmugam S. P., Nurni V. N., Manjini S., Chandra S., Holappa L. E. K. Challenges and outlines of steelmaking toward the year 2030 and beyond–Indian perspective. *Metals*. 2021. Vol. 11. No. 10. 1654. https://doi.org/10.3390/met11101654
4. Zhou D., Xu K., Lv Z., Yang J., Li M. He F., Xu G. Intelligent manufacturing technology in the steel industry of China: a review. *Sensors*. 2022. Vol. 22. No. 21. 8194. https://doi.org/10.3390/s22218194
5. Dai Z., Sun Y., Liu W., Yang S., Li J. Smelting stage recognition for converter steelmaking based on the convolutional recurrent neural network. *International Journal of Minerals, Metallurgy and Materials*. 2025. Vol. 32. P. 2152–2163. https://doi.org/10.1007/s12613-024-3086-2
6. Backman J., Kyllönen V., Helaakoski H. Methods and tools of improving steel manufacturing processes: Current state and future methods. *IFAC-PapersOnLine*. 2019. Vol. 52. No. 13. P. 1174–1179. https://doi.org/10.1016/j.ifacol.2019.11.355
7. Jiang S.-L., Shen X., Zheng Z. Gaussian process-based hybrid model for predicting oxygen consumption in the converter steelmaking process. Processes. 2019. Vol. 7. No. 6. 352. https://doi.org/10.3390/pr7060352

8. Shao X., Liu Q., Xin Z., Zhang J., Zhou T., Li S. Hybrid model for BOF oxygen blowing time prediction based on oxygen balance mechanism and deep neural network. *International Journal of Minerals, Metallurgy and Materials*. 2024. Vol. 31. P. 106–117. https://doi.org/10.1007/s12613-023-2670-1
9. Torabi Rad M., Viardin A., Schmitz G. J., Apel M. Theory-training deep neural networks for an alloy solidification benchmark problem. *Computational Materials Science*. 2020. Vol. 180. 109687. https://doi.org/10.1016/j.commatsci.2020.109687
10. Kizhakkinan U., Duong P. L. T., Laskowski R., Vastola G., Rosen D. W., Raghavan N. Development of a surrogate model for high-fidelity laser powder-bed fusion using tensor train and gaussian process regression. *Journal of Intelligent Manufacturing*. 2023. Vol. 34. P. 369–385. https://doi.org/10.1007/s10845-022-02038-4
11. Demeter J., Bul'ko B., Demeter P., Hrubovčáková M. Evaluation of factors affecting the MgO–C refractory lining degradation in a basic oxygen furnace. *Applied Sciences*. 2023. Vol. 13. No. 22. 12473. https://doi.org/10.3390/app132212473
12. Bellemans I., Zietsman J., Verbeken K. Fundamental and formation aspects of slag freeze linings: a review. *Journal of Sustainable Metallurgy*. 2022. Vol. 8. P. 64–90. https://doi.org/10.1007/s40831-022-00505-z
13. Liu L., Kuangdi X. Slag splashing technology. In: Xu K. (eds.). *The ECPH Encyclop/edia of Mining and Metallurgy. Sin/gapore*: Springer, 2023. P. 1–2. https://doi.org/10.1007/978-981-19-0740-1_993-1
14. Santos I. A. S., de Medeiros Santos V. R., dos Reis Lima W., da Silva A. L., Maia B. T., de Oliveira J. R. Slag splashing: simulation and analysis of the slags conditions. *Journal of Materials Research and Technology*. 2019. Vol. 8. No. 6. P. 6173–6176. https://doi.org/10.1016/j.jmrt.2019.10.011
15. Yang G., Li B., Sun M., Qin D., Zhong L. Numerical simulation of the slag splashing process in a 120 ton top-blown converter. *Metals*. 2023. Vol. 13. No. 5. 940. https://doi.org/10.3390/met13050940
16. Sinelnikov V., Szucki M., Merder T., Pieprzyca J., Kalisz D. Physical and numerical modeling of the slag splashing process. *Materials*. 2021. Vol. 14. No. 9. 2289. https://doi.org/10.3390/ma14092289
17. Sinelnikov V. O., Kalisz D., Zak P. L., Kuzemko R. D. Power increase of supersonic jets in oxygen converter. In: *IOP Conference Series: Materials Science and Engineering. 5th International Conference Recent Trends in Structural Materials, November 14–16, 2018, Pilsen, Czech Republic*. Vol. 461. 012078. http://dx.doi.org/10.1088/1757-899X/461/1/012078
18. Leão P. M. G. C., Rodrigues E. F., da Silva C. A., da Silva I. A., Seshadri V. Influence of physical properties of slag and operational parameters on slag splashing process in an oxygen convertor. In: Reddy R. G., Chaubal P., Pistorius P. C., Pal U. (eds.). *Advances in Molten Slags, Fluxes, and Salts: Proceedings of the 10th International Conference on Molten Slags, Fluxes and Salts 2016*, Cham: Springer, 2016. P. 1043–1051. https://doi.org/10.1007/978-3-319-48769-4_111
19. Zhang H., Liu K., Zhao H., Tian Y., Liang J., Yuan Z. Numerical simulation of innovative slag splashing process in a converter using a nozzle-twisted oxygen lance. *Journal of Sustainable Metallurgy*. 2024. Vol. 10. P. 864–879. https://doi.org/10.1007/s40831-024-00836-z
20. Zhang H., Yuan Z-f., Zhao H-h., Xu B-s., Liu K., Mei L., Ma B-w. Numerical simulation of CO2 used for slag splashing process in converter. *Steel Research International*. 2023. Vol. 94. No. 10. 2300025. https://doi.org/10.1002/srin.202300025
21. Zhulkovskyi O., Panteikov S., Zhulkovska I., Kashcheev M., Leshchenko E. Heat transfer calculation for numerical simulation of thermal mode of slag-splashing lance in the forecasting system. In: Kazymyr V., Morozov A., Palagin A., Shkarlet S., Stoianov N., Vinnikov D., Zheleznyak M. (eds.). *Mathematical Modeling and Simulation of Systems (MODS 2023). Lecture Notes in Networks and Systems*. Cham: Springer, 2024. Vol. 1091. P. 70–81. https://doi.org/10.1007/978-3-031-67348-1_6
22. Zhulkovskii O. Temperature conditions for operation of top-mounted BOF lance barrel. *Steel in Translation*. 1998. Vol. 28. No. 7. P. 37–39. https://www.scopus.com/pages/publications/33751383079

23. Zhulkovskii O., Panteikov S., Zhulkovskaya I. Information-modeling forecasting system for thermal mode of top converter lance. *Steel in Translation*. 2022. Vol. 52. No. 5. P. 495–502. https://doi.org/10.3103/S0967091222050138
24. Zhulkovskyi O. Unification of approaches to the numerical solution of the boundary value problem for heat conduction using TDMA. *Energetika*. 2025. Vol. 71. No. 1. P. 63–77. https://doi.org/10.6001/energetika.2025.71.1.5
25. Ford W. Algorithms. In: *Numerical Linear Algebra with Applications*. Elsevier, 2015. P. 163–179. https://doi.org/10.1016/B978-0-12-394435-1.00009-0
26. Rapp B.E. Numerical methods for linear systems of equations. In: *Microfluidics: Modelling, Mechanics and Mathematics*. Elsevier, 2017. P. 497–535. https://doi.org/10.1016/b978-1-4557-3141-1.50025-3
27. Alsuwaiyel M. H. Parallel algorithms. In: *Lecture Notes Series on Computing*. Vol. 16. New Jersey: World Scientific, 2022. https://doi.org/10.1142/12744
28. Modest M. F., Mazumder S. *Radiative Heat Transfer*. Academic Press, 2021. https://doi.org/10.1016/C2018-0-03206-5
29. Wickström U. Heat transfer by radiation. In: *Temperature Calculation in Fire Safety Engineering*. Cham: Springer, 2016. https://doi.org/10.1007/978-3-319-30172-3_5
30. Howell J. R., Mengüc M. P., Daun K., Siegel R. *Thermal Radiation Heat Transfer*. CRC Press, 2020. https://doi.org/10.1201/9780429327308
31. Lienhard V J. H., Lienhard IV J. H. *A Heat Transfer Textbook*. Cambridge, MA: Phlogiston Press, 2024. https://ahtt.mit.edu
32. Panteikova E., Panteikov S., Zhulkovskyi O., Zhulkovska I., Pieieva I. Development of the slag-splashing lance for slag skull coating the converter lining. In: Altenbach H., Gao X-W., Syngellakis S., Cheng A.H.-D., Lampart P., Tkachuk A. (eds.). *Advances in Mechanical and Power Engineering II, CAMPE 2023, Lecture Notes in Mechanical Engineering*. Cham: Springer, 2025. P. 143–152. https://doi.org/10.1007/978-3-031-82979-6_15
33. Andreiana D. S., Galicia L. E. A., Ollila S., Guerrero C. L., Roldán Á. O., Navas F. D., del Real Torres A. Steelmaking process optimised through a decision support system aided by self-learning machine learning. *Processes*. 2022. Vol. 10. No. 3. 434. https://doi.org/10.3390/pr10030434
34. Roldán Á. O., Gassner G., Schlautmann M., Galicia L. E. A., Andreiana D. S., Heiskanen M., Guerrero C. L., Navas F. D., del Real Torres A. Optimisation of operator support systems through artificial intelligence for the cast steel industry: A case for optimisation of the oxygen blowing process based on machine learning algorithms. *Journal of Manufacturing and Materials Processing*. 2022. Vol. 6. No. 2. 34. https://doi.org/10.3390/jmmp6020034

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SKAITINIS ŠLAKO PURŠKIMO IETIES ŠILUMINIO REŽIMO MODELIAVIMAS BAZINIO DEGUONIES KONVERTERIO IŠKLOJOS KARŠTOJO REMONTO METU

Santrauka

Skaitinis modeliavimas tampa vis svarbesnis tobulinant labiausiai paplitusį ir efektyviausią plieno gamybos procesą baziniuose deguonies konverteriuose (BOF). Aktualia BOF proceso problema išlieka būtinybė didinti viršutinio pūtimo konverterio ugniai atsparios išklojos ilgaamžiškumą. Vienas pažangiausių konverterio išklojos karštojo remonto metodų yra ugniai atsparių medžiagų tarpusavio sulydymo šlakavimo technologija, sukurianti patvarią apsauginę dangą (sluoksnį). Esminis uždavinys įgyvendinant progresyvų šlako purškimo procesą yra užtikrinti tinkamą ir stabilų naudojamų šlako purškimo iečių patvarumą.

Sukurtas viršutinio vandeniu aušinamo šlako purškimo ieties korpuso terminio režimo matematinis modelis, skirtas konverterio išklojos karštojo remonto metu naudojant šlako purškimo metodą. Skaitiškai ištirti šilumos pernašos dėsningumai ir temperatūros pokyčiai išoriniame šlako purškimo ieties vamzdyje, naudojant dvi pagrindines pūtimo įrenginių konstrukcijas, eksploatuojamas tipinėse 160 tonų ir 250 tonų talpos viršutinio pūtimo konverterių išklojos šlakavimo technologinėmis sąlygomis. Gautos regresinės priklausomybės šlakopurškimo ieties korpuso terminiam režimui įvertinti, esant skirtingiems aušinimo vandens srautams.

Gauti rezultatai naudojami projektuojant šlako purškimo ietį ir kuriant jos eksploatavimo technologiją 250 tonų talpos viršutinio pūtimo konverterio išklojos karštojo remonto metu taikant šlakavimo metodą. Rezultatai prisideda prie automatizuoto projektavimo sistemų kūrimo ir tobulinimo, šlako purškimo iečių modernizavimo bei deguonies konverterio plieno gamybos valdymo. Taip pat rezultatai padeda kurti bei tobulinti automatizuotas projektavimo ir modernizavimo sistemas bei spręsti šlako purškimo iečių terminio režimo optimizavimo ir prognozinės analizės uždavinius deguonies konverterio plieno gamybos kontrolės kontekste.

Reikšminiai žodžiai: deguonies konverteris, šlako purškimo procesas, šlako purškimo ietis, ieties patvarumas, terminis režimas, skaitinis modeliavimas