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DETERMINING THE HEAT AND MASS TRANSFER PATTERNS IN THE TUNDISH OF A CONTINUOUS CASTING MACHINE

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This study's object is the thermal state of the tundish ladle in a continuous billet casting machine, aimed at prolonging the duration of the series of melts.

This paper reports the numerical modeling of the heat and mass transfer processes in the tundish ladle of a continuous billet casting machine (CCM). The model takes into account the hydrodynamics of liquid steel, as well as the temperature distribution in the multilayer lining and the ladle casing; it also makes it possible to predict local wear of the lining based on the analysis of the technological parameters of the process and the chemical composition of steel. Special attention is paid to the study of the temperature and turbulent characteristics of the flow, the residence time of the steel in the ladle, and the influence of its composition on the intensity of destruction of the lining layers.

The results make it possible to localize critical areas of thermal and mechanical overload of the ladle lining, in particular the contact zones of the liquid steel jet and the wall areas near the turbos tops, where the following are recorded: shear stress up to 275 Pa; turbulent kinetic energy over 0.14 m^2/s^2; and metal temperature up to 1830 K.

The local wear map built shows the distribution of the lining erosion rate within 2.4–4.3 mm/h depending on the hydrodynamic and chemical conditions. The predictive model combines CFD parameters, the chemical composition of steel, and the pouring speed, which showed high accuracy confirmed by the coefficient of determination $R^2 = 0.99937$.

A feature of the result is the comprehensive combination of local flow conditions and steel composition with the erosion model, which has made it possible to give engineering-based recommendations for optimizing the ladle operating modes.

The developed predictive model of liner wear rate could be used to monitor its condition, improve ladle operating modes, and increase the reliability of the continuous casting process

Keywords: tundish, continuous casting of billets, liner, CFD modeling, SHAP analysis, machine learning

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1. Introduction

Current technological requirements for continuous steel casting impose increasingly stringent conditions on the stability of the temperature regime and the service life of the tundish ladle lining. In the process of serial casting, liquid steel enters the tundish ladle where intensive heat and mass transfer occurs, which is accompanied by complex hydrodynamic phenomena: the formation of vortices, stagnant flow zones, uneven mixing, and local overheating. These processes significantly affect the quality of the billets, wear of the lining, and the duration of continuous casting.

Particular importance is attached to the temperature state of the metal shell of the ladle. The key factor in reliability is local wear of the lining, which depends on the interaction of steel flows with the refractory lining, the geometry of the ladle, the intensity of turbulent flows, and the composition of the metal.

In this regard, numerical modeling based on finite element methods and computational fluid dynamics (CFD) becomes an indispensable tool for analyzing and predicting the thermal state of the ladle. Using the ANSYS CFX software environment makes it possible to take into account not only the complex hydrodynamics of the melt and heat transfer in a multilayer lining but also integrate the chemical composition of the steel, the distribution of speeds, temperatures, and turbulent characteristics. This opens up the possibility not only to assess the thermomechanical resource of the lining but also build predictive models of its erosion wear using machine learning methods.

Given the above, a relevant task is to conduct numerical modeling of heat and mass transfer in the tundish ladle taking into account real operating conditions, temperature distribution, hydrodynamic features of the flow, and erosion wear of the lining. In the future, this will allow for accurate prediction of the lining resource, timely planning of ladle maintenance, improvement of steel pouring modes, and for improving the overall efficiency and safety of the continuous casting machine.

2. Literature review and problem statement

The authors of work [1] report the results of numerical modeling of the formation and removal of exogenous non-metallic inclusions in a two-jet ladle. It is shown that the largest number of inclusions is formed in the turbulent inhibitor zone and on the inner surface of the long nozzle, and the efficiency of their removal reaches up to 80% at the optimal pouring speed of 1.2 m/min. However, the issues related to the accurate description of the interaction of inclusions with the lining walls under different turbulence regimes remain unresolved. The likely reason is the objective limitations associated with the insufficient volume of experimental data and the complexity of reverse verification under real conditions. An option to overcome these difficulties may be the integration of the model with industrial data on the residual lining thickness and validation of the results.

Paper [2] reports the results of a combination of laboratory (hydraulic) modeling and 3D numerical analysis of lining erosion in a ladle. An empirical relationship between the erosion rate and flow characteristics (turbulent kinetic energy and tangential stress) is proposed. It is shown that the main erosion occurs inside the turbulent inhibitor, after which it sharply weakens. However, the features of the thermal interaction with the lining, as well as the influence of the steel composition on the aggressiveness of the medium, were not considered. The likely reason is the complexity of simulating heat transfer in a water model. A possible direction of development may be thermo-hydrodynamic modeling taking into account the aggressiveness of the components. This is the approach used in [1] but it was not supplemented by an experimental component, which leaves the question open.

The authors of [3] investigated various configurations of stop pipes and their influence on multipoint flow in a four-jet sluice. Numerical and physical models have shown that the use of bell-shaped configurations reduces the maximum flow velocity and increases the volume of plug-flow zones from 6.6% to 9.0%. This reduces level fluctuations in the casting zone and increases process stability. However, the effect on thermal fields and lining wear has not been considered. The fundamental limitation is the simplified flow modeling without taking into account heat transfer and interaction with the lining. A possible solution may be to supplement the model with calculations of temperature fields and thermal stresses in the lining material, as well as their relationship with wear, as proposed in [2].

In [4], a combined model for predicting the melt temperature in the tundish during continuous casting was built, which is based on a combination of a mechanistic approach and machine learning (modified PINN algorithm). The proposed solution made it possible to take into account dynamic changes in the thermal properties of the lining and achieve an average prediction accuracy of 2.1 K. It is shown that the model demonstrates higher accuracy compared to conventional mechanisms and purely empirical models. However, there is no connection with the processes of lining degradation and their impact on heat transfer. Objective difficulties are the complexity of parameterizing thermal wear and local defects. An option to overcome them may be to combine the temperature model with the erosion model, which would make it possible to predict the lining resource simultaneously with the temperature parameters of the metal.

In [5], methods for determining unknown quantities in the analysis of research are presented: experimental and numerical calculation of mathematical models. It is shown that experimental approaches, although they give realistic results, require complex equipment and have scalability limitations. An alternative is numerical methods, which are less expensive and make it possible to simulate mixing and heat transfer. However, such models require verification and tuning, especially for complex flow regimes and interaction with the lining, which is confirmed in work [6].

Hydrodynamic phenomena in the ladle (vortices, flooded jets, etc.) are considered in detail in [7], where it is shown that their consideration is necessary for the design of the device but there is no universal way to relate them to the quality of steel. This is explained by the fact that such phenomena are difficult to formalize within a single model. Among the numerical methods, the most widespread are the finite difference and finite element methods [8]. The first makes it possible to solve problems by approximating differential equations on a grid, the second – by discretizing the volume and using stiffness matrices. The latter is particularly effective for heat and mass transfer problems [9]. However, these methods are quite sensitive to boundary conditions and require adaptation to specific tundish configurations.

In addition, studies by many other authors [10, 11] confirmed that the key factor of the stability of the continuous casting process is the thermal regime of the tundish. Exceeding the lining temperature above 330–350°C under conditions of long-term operation leads to accelerated wear of the lining [12], which justifies the feasibility of numerical modeling of the thermal state of the ladle to predict the lining resource. Notably, the problems of quantitatively predicting the residual lining resource in real time remain unsolved. The likely reason is the difficulties of measuring the temperature in critical zones and the lack of a model that takes into account local heat flows. An option for overcoming them is to use CFD modeling with reference to the data on the casing temperature map.

From the above review [1–14], taking into account the current state of the metallurgical products market, we can conclude that the steelmaking processes are becoming increasingly complex and require more efficient tools. Our review of the literature reveals insufficient attention to spatial assessment of the thermal state of the tundish ladle lining, in particular, taking into account local hydrodynamic and thermal loads. Most of the cited works are dominated by either a simplified idea of heat transfer, or consideration of individual aspects of hydrodynamics without comprehensive consideration of their impact on lining wear. The relationship between the technological parameters of pouring, the chemical composition of steel and local erosion of the lining has not been sufficiently studied. All this indicates the feasibility of conducting a study aimed at modeling heat and mass transfer in the tundish ladle, taking into account the complex impact of temperature, mechanical and chemical factors on lining wear.

3. The aim and objectives of the study

The aim of our research is to improve the efficiency of the continuous casting machine by building a model of heat and mass transfer in the tundish. This will make it possible to predict the wear of the ladle lining and improve the steel pouring regimes under actual operating conditions.

To achieve this aim, the following objectives were accomplished:

– to perform numerical simulation of hydrodynamics, heat and mass transfer in the tundish, taking into account turbulence and temperature fields;

– to assess the erosion wear of the lining based on mechanical, thermal, and chemical influences, including the influence of the steel composition;

– to build a predictive model of wear of the tundish lining.

4. The study materials and methods

The object of our study is the thermal state of the tundish of a continuous billet casting machine, aimed at prolonging the duration of a series of melts. A 6-jet tundish of a continuous billet casting machine for the conditions at PAT "ArcelorMittal Kryvyi Rih" (Ukraine) was considered. Intensive heat and mass transfer processes occur in it between liquid steel, a multilayer lining, and a metal casing.

Local wear of the lining depends not only on the operating time but also on changes in thermal, hydrodynamic, and chemical loads, which can be detected using CFD modeling and statistical analysis. Our study adopted simplifications, in particular, the geometry of the ladle model without local defects, cracks, protrusions, and wear of the lining, as well as assumptions – the chemical interaction of steel with the lining.

Using the ANSYS software package [15] makes it possible to take into account the distribution of temperatures, velocities, turbulence, and stagnation zones of the melt during modeling. Hence, the construction of the mathematical model was performed on the basis of ANSYS, within the CFX module, which implements the finite element method (FEM) in the context of computer modeling of hydrodynamic processes (CFD – Computational Fluid Dynamics). The considered model was unstable (unsteady), turbulent, with a single-phase representation of the steel melt.

The basic physical phenomena that are expedient to describe using mathematical modeling include:

– introduction of a free stream of steel into the tundish bath and its interaction with the bottom of the ladle;

– formation of zones of convective motion and the emergence of "dead zones" in which the movement of steel is practically absent;

– estimation of the steel residence time in the ladle depending on its geometry and the placement of partitions and turbochargers;

– behavior of liquid steel during the initial stage of pouring, as well as the decrease and restoration of the steel level in the ladle during the replacement of the steel casting ladle;

– determination of lining zones prone to erosion caused by steel flows;

– outflow of steel through the steel casting openings of the tundish into the molds of the continuous casting machine (CCM).

In our study, a complex model was used that combines CFD calculation of the hydrodynamics of liquid steel, solution to the energy equation to determine the temperature field, and a statistical model to estimate the erosion wear of the lining. To implement the hydrodynamic part, ANSYS CFX was used with turbulent flow according to the *k*–*ε* model. The temperature calculation was performed taking into account heat transfer in the multilayer ladle lining and limiting the heat flow to the outer surface.

The continuity equation and the equation of motion after averaging (according to the Reynolds approach) and using the Boussinesq turbulent viscosity approximation to relate Reynolds stresses to the main flow velocity strain tensor take the form:

$$\frac{\partial \rho}{\partial t}+\frac{\partial\left(\rho U_j\right)}{\partial x_j}=0, \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho U_i\right)+\frac{\partial}{\partial x_j}\left(\rho U_i U_j\right)=$$
$$=-\frac{\partial \rho}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\right]-\rho_{ref}g\beta\left(T-T_{ref}\right), \tag{2}$$

where ρ is the density of the liquid, kg/m^3; U_i, U_j are the components of the velocity vector, m/s; t is time, s; p is the pressure, Pa; x_i, x_j are the spatial coordinates, m; ρ_{ref} is the reference density, kg/m^3; g is the acceleration of gravity, m/s^2; T is the temperature, K; T_{ref} is the reference temperature, K; μ_{eff} is the effective viscosity, Pa·s, which is defined as

$$\mu_{eff}=\mu+\mu_t, \tag{3}$$

where μ is the dynamic viscosity, Pa·s; μ_t is the turbulent viscosity, Pa·s.

To model the turbulent characteristics, the turbulence model was used: *k*–*ε*.

Turbulent k–ε model. The *k*–*ε* model assumes that the turbulent viscosity is related to the turbulent kinetic energy *k* and the turbulent energy dissipation rate *ε* by the following relationship

$$\mu_t=C_\mu\frac{k^2}{\varepsilon}, \tag{4}$$

where μ_t is the turbulent viscosity, Pa·s; C$_\mu$ is the empirical model coefficient (≈ 0.09); k is the turbulent kinetic energy, m^2/s^2; ε is the turbulent energy dissipation, m^2/s^3. The values of k and ε are determined using two transfer equations:

$$\frac{\partial\left(\rho k\right)}{\partial t}+\frac{\partial\left(\rho U_j k\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial_k}{\partial x_j}\right]+P_k-\rho\varepsilon, \tag{5}$$

$$\frac{\partial\left(\rho\varepsilon\right)}{\partial t}+\frac{\partial\left(\rho U_j\varepsilon\right)}{\partial x_j}=$$
$$=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+C_{\varepsilon 1}\frac{\varepsilon}{k}P_k-C_{\varepsilon 2}\frac{\varepsilon^2}{k}, \tag{6}$$

C_μ, $C_{\varepsilon1}$, $C_{\varepsilon2}$, σ_k, σ_ε are empirical constants recommended by Launder and Spaulding [16]; P_k is the source of turbulent energy due to viscous forces, W/m^3.

In the process of heat transfer modeling, three main physical mechanisms of temperature change were taken into account: convection, radiation, and heat transfer together with mass transfer.

Convective heat transfer *QC* is defined as

$$QC=\pi d\lambda\mathrm{Nu}\left(T_G-T\right), \tag{7}$$

where *QC* is the heat flux, W; λ is the thermal conductivity of the fluid, W/m K; T_G and T are the temperatures of the fluid and particles, respectively, K; Nu is the Nusselt number, which is given as

$$\mathrm{Nu}=2+0.6Re^{0.5}\left(\frac{\mu C_p}{\lambda}\right)^{1/3}, \tag{8}$$

where C_p is the specific heat capacity of the liquid, J/(kg·K); μ – dynamic viscosity, Pa·s; *Re* – Reynolds number.

For multiphase reactions, convective heat transfer is corrected for mass transfer (the drag coefficient and the argument of the exponent are dimensionless quantities)

$$QC=QC\cdot\zeta\cdot\frac{e^{-\zeta}}{1-e^{-\zeta}}, \tag{9}$$

where ζ is determined from

$$\zeta = C_p \cdot \left|\frac{dm}{dt}\right| \cdot \frac{1}{\pi d \lambda Nu}, \qquad (10)$$

where dm/dt is the total mass transfer rate of the particle, kg/s.

The heat transfer associated with mass transfer QM is defined as

$$QM = \sum\left(\frac{dm_C}{dt}\right) \cdot V, \qquad (11)$$

where $\sum\left(dm_C/dt\right)$, kg/s; the sum is taken over all components of the particle for which heat transfer occurs; V is the velocity, m/s.

The radiation heat transfer Q_R for a particle with diameter d_p, with uniform temperature T_p and emissivity ε_p, is determined from the following formula

$$Q_R = \varepsilon_p \pi d_p^2 \left[\pi I - \sigma n^2 T_p^4\right], \qquad (12)$$

where I is the radiation intensity on the surface of the particle at its location, W/m^2; n is the refractive index of the medium (liquid); σ is the Stefan-Boltzmann constant, W/(m^2·K^4).

An equivalent amount of heat can be absorbed or emitted by the particle through the radiation field.

The rate of change in the temperature of the particle is defined as

$$\sum\left(m_c C_p\right)\frac{dT}{dt} = Q_C + Q_M + Q_R, \qquad (13)$$

Σ – all components of the particle, including those not undergoing mass transfer; m_C – mass of the particle component, kg; C_P – specific heat capacity, J/kg·K; dT/dt – rate of temperature change, K/s; QC – heat received through convection, W; QM – heat associated with mass transfer, W; QR – heat transferred through radiation, W.

The general structure of the erosion model is derived experimentally; a complex function of many factors that determine both mechanical and chemical and thermochemical wear. The general formula is

$$ER = f\left(\tau_w, T_{steel}, v, \varepsilon, \omega, q, h, Chem\right). \qquad (14)$$

To determine the heat transfer from the liquid steel flowing through the tundish to its outer wall (the heating of which determines the duration of the casting series), the calculation of the non-stationary heat conduction equation in one-dimensional form was used

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}, \qquad (15)$$

where T is the layer temperature, K; t is time, s; x is the spatial coordinate in the direction of heat transfer, m; $\alpha = \lambda/\rho C_p$ is the thermal conductivity of the layer, m^2/s.

The solution is derived by the finite difference method with an explicit scheme for internal nodes (except for the extreme ones)

$$T_i^{n+1} = T_i^n + \alpha_i \frac{\Delta t}{\Delta x^2}\left(T_{i+1}^n - 2T_i^n + T_{i-1}^n\right). \qquad (16)$$

The transfer of heat from steel is modeled by a condition of the 1st kind (Neumann type), through the following ratio

$$T_0^{n+1} = T_0^n + \frac{\alpha_{steel}\left(T_{steel} - T_0^n\right) \cdot \Delta t}{\rho_0 C_{p0}}. \qquad (17)$$

The right boundary of the model of contact of the casing of an intermediate bucket from air is calculated according to a modified scheme that takes into account external heat transfer

$$T_{N-1}^{n+1} = \left(\frac{1 - \dfrac{h}{\lambda \Delta x} T_{N-1}}{1 - \dfrac{h}{\lambda}}\right) T_{air}. \qquad (18)$$

To determine the stability of the system during the calculation, the Courant criterion (CFL) is applied in the program code, according to which each node of the system is checked for compliance with the following condition

$$r = \frac{\alpha \cdot \Delta t}{\Delta x^2}. \qquad (19)$$

The model takes into account the real material properties of each layer, adaptive spatial step, exact boundary condition on the steel side and heat transfer at the outer boundary. This makes it possible to take into account the thermal resistance of the multilayer ladle lining and estimate the temperature in each layer in dynamics.

For each measurement point, the multilayer characteristics of the lining were taken into account, in particular the initial and final thickness of the reinforcement layer, thermal insulation plate and shotcrete. Measurements were carried out by placing a template of a given geometry in the internal volume of the intermediate ladle, relative to which the distances to the lining surface at the control points were determined using a laser tape measure. This approach provided the possibility of objective assessment of local changes in the lining thickness after each series of pouring.

CFD modeling was performed in a suitable software environment, which makes it possible to determine the dependence of local flow characteristics (pressure, shear stress, heat flux, turbulent kinetic energy, velocity in the wall zone, etc.) on the steel temperature and casting speed. For each plane, CFD parameter regression was performed, which yields analytical equations of dependence on T_{steel} and V_{cast}.

By integrating these parameters, a single data frame was formed, in which each row corresponds to a separate measurement point. The features include the chemical composition of the steel (C, Mn, Si, S, P, Al, Ca, N_2), the Mn/S and Mn/Si ratios, the steel temperature, the casting speed, the mass flow rate of the metal, as well as CFD parameters calculated individually for each point depending on its location plane.

To build the predictive model, a classical multivariate linear regression was used, supplemented by its modification using machine learning methods and validation on an independent sample. To assess the contribution of individual parameters to the formation of the initial result, an analysis of the importance of the features was carried out, in particular using the SHAP method, which makes it possible to interpret the influence of each variable. In order to compare the accuracy of the model, alternative approaches were also tested – Random Forest and Gradient Boosting; however, it was the linear regression model that demonstrated the best fit to the empirical data, which is explained by the linear structure of the studied process and the limited volume of the training sample.

The end result of the constructed model is to determine the influence of a combination of hydrodynamic, thermal, and chemical factors on the dynamics of the temperature increase in the metal casing of the tundish, which, in turn, determines the maximum duration of a series of continuous steel casting in the long-length CCM.

5. Results of numerical simulation of heat and mass transfer in the tundish

5. 1. Hydrodynamics, heat and mass transfer in the tundish

The result of numerical simulation is the determination of the main factors at each nodal point of the computational domain for each time step:

– fields of velocity distribution of liquid steel in the tundish, which makes it possible to determine the nature of the flow (laminar or turbulent) and the zone of stagnation or excessive activity and the dependence of basic technological factors on the dynamics of the distribution of flow velocity vectors;

– temperature fields in the entire volume of the ladle and in the lining layers, which makes it possible to estimate the thermal loads on the walls, the possibility of thermal damage, as well as the effectiveness of thermal insulation;

– fields of turbulent characteristics (turbulent kinetic energy, dissipation, turbulence frequency), which are used to estimate the intensity of metal mixing and erosion load on the walls;

– tracer concentration distribution, which makes it possible to estimate the residence time (RTD) of the metal in the ladle, the mixing efficiency, and the influence of the structural elements (Turbos tops and structural features of the tundish ladle) on the flow.

These results are shown graphically in Fig. 1–7.

One of the most representative modeling results is the identification of zones of active convective mixing of steel, which is of fundamental importance for ensuring the stability of the temperature field and homogeneity of steel during the casting of ultra-long series, especially in the near-wall zones of the ladle.

5. 2. Assessment of ladle lining erosive wear

The map of local wear of the lining, shown in Fig. 8, was constructed by integrating the results of CFD modeling with technological actual and chemical parameters of the process. In particular, the modeling process took into account the hydrodynamic characteristics of the liquid steel flow, including wall shear stress (WWS) (from 0.05 to 0.45 Pa); turbulent kinetic energy (from 9.7×10^{-4} to 1.6×10^{-3} m^2/s^2); turbulence dissipation (from 2.5×10^{-3} to 5.4×10^{-3} m^2/s^3).

The model also takes into account such parameters as metal temperature (from 1791 to 1830 K); heat flux (from 6941 to 7350 W/m^2); flow velocity (from 0.015 to 0.079 m/s); Mn/Si ratio (1.8–6.2) and Mn/S (20–140), which affect the aggressiveness of the melt.

The map of local lining wear (erosion) is shown in Fig. 8.

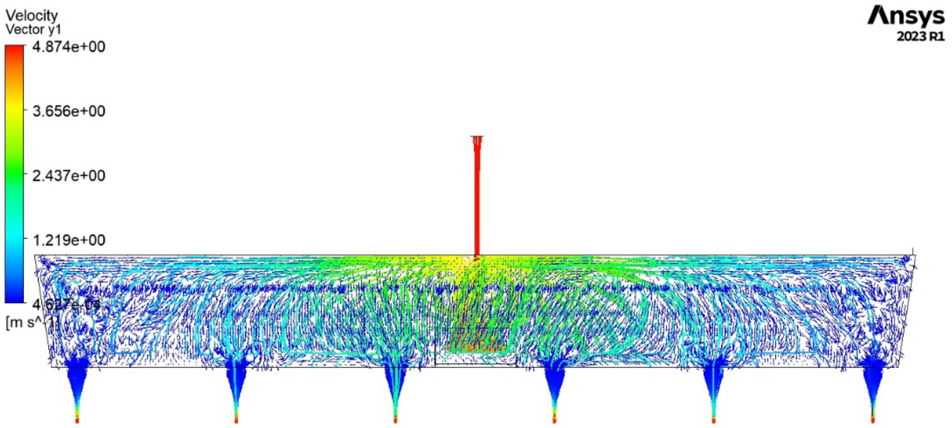

Fig. 1. Vector velocity distribution in a cross section passing through 6 exits, under conditions of a metal level of 0.85 m during bucket filling

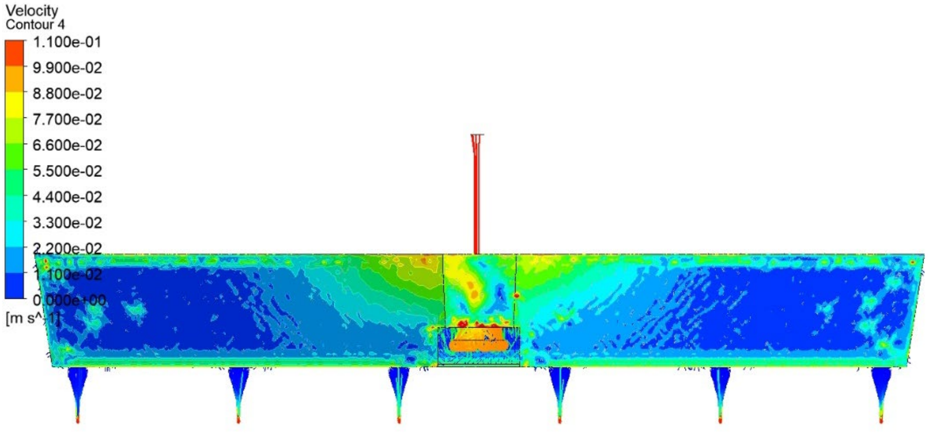

Fig. 2. Flow velocity distribution in the near-wall zones of the tundish

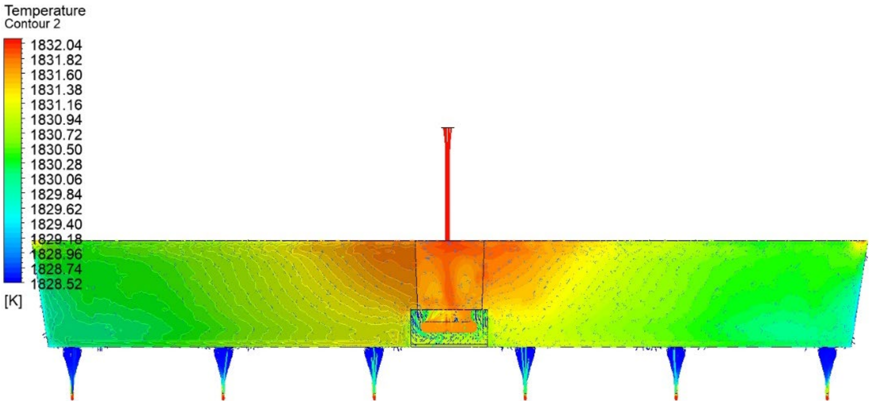

Fig. 3. Distribution of temperature fields in the near-wall zones of the tundish

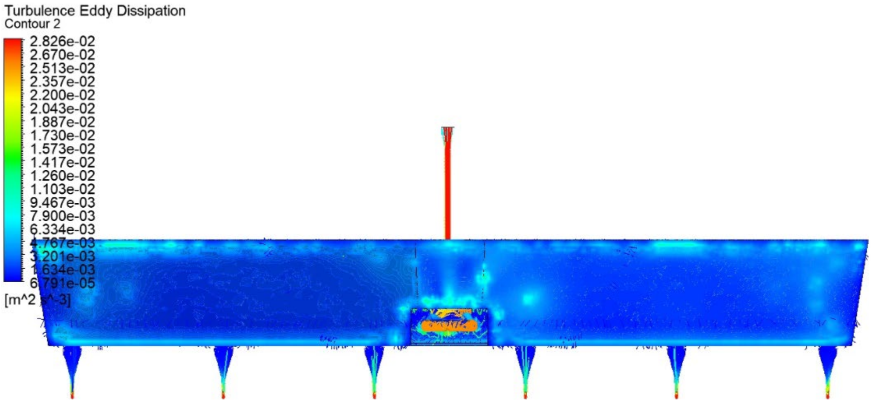

Fig. 4. Distribution of turbulent dissipation in the near-wall zones of the tundish

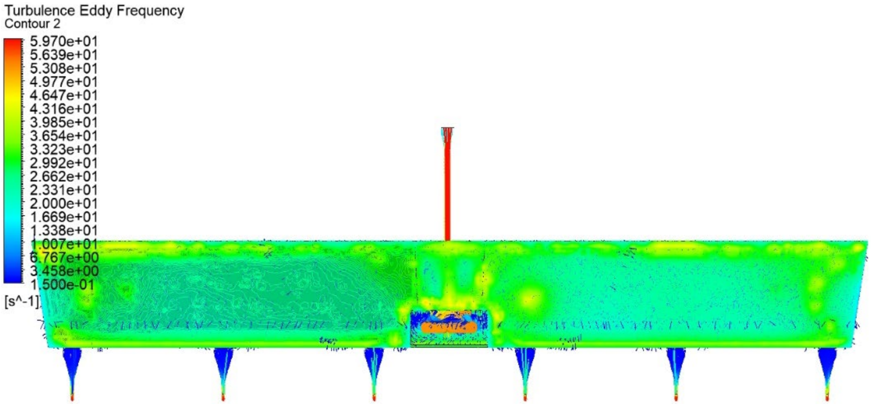

Fig. 5. Turbulence frequency distribution in the near-wall zones of the tundish

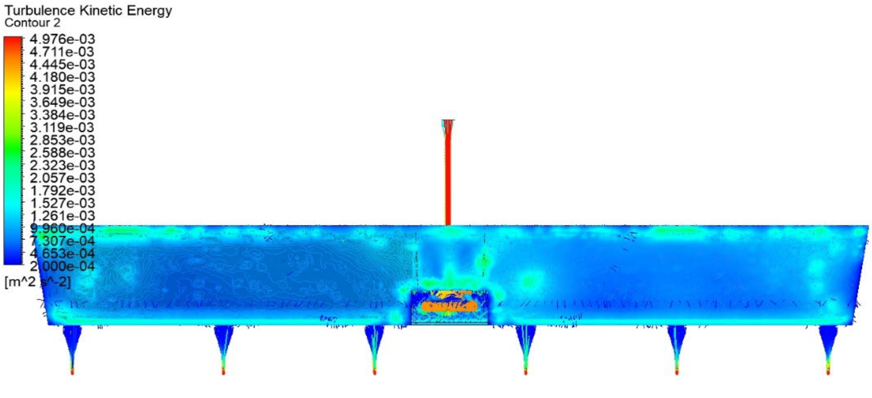

Fig. 6. Distribution of turbulent kinetic energy in the near-wall zones of the tundish

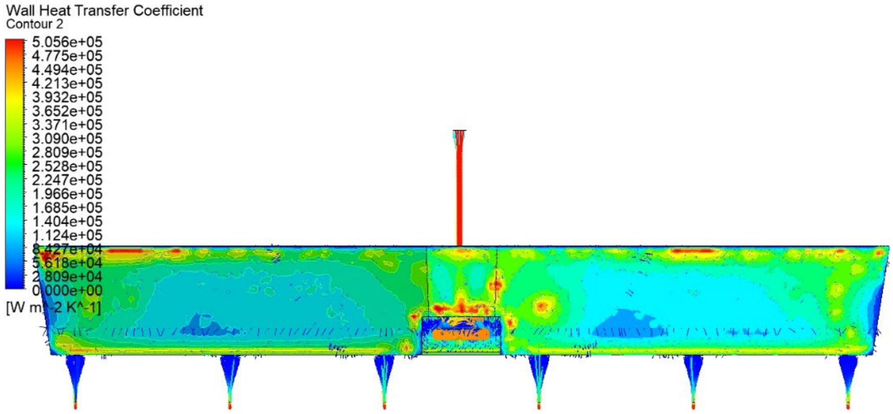

Fig. 7. Heat transfer distribution on the walls of the tundish

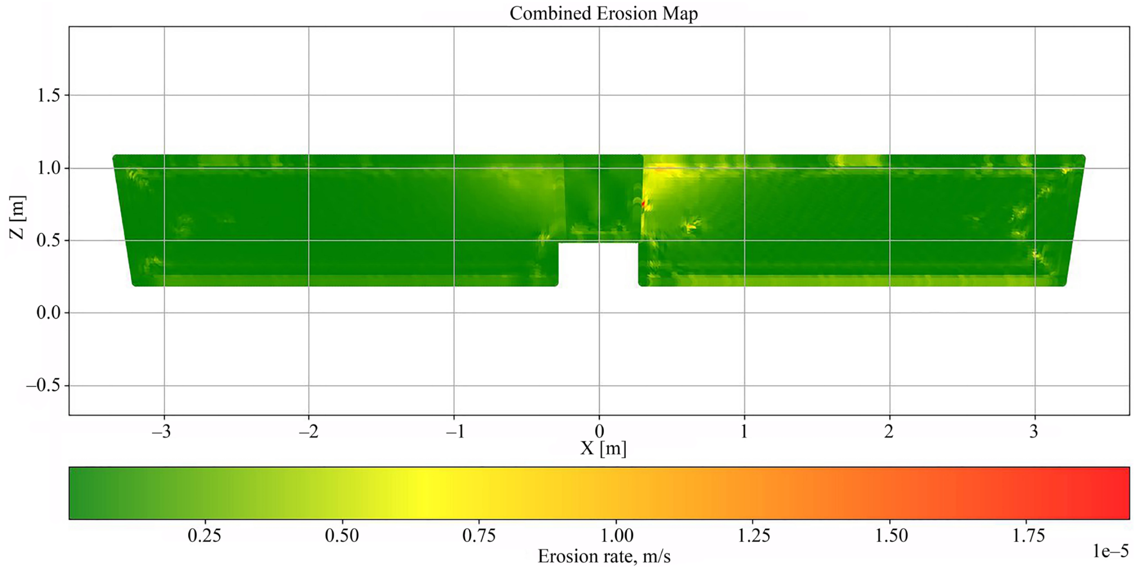

Fig. 8. Map of local wear (erosion) of the lining

For ease of interpretation, the following spatial coordinates are used in the figure: x – bucket height, z – bucket width. The presented map of local lining wear demonstrates the uneven distribution of erosion in the horizontal and vertical planes of the bucket, which visualizes the localization of zones of greatest influence of hydrodynamic and chemical factors. Owing to this comprehensive approach, it became possible to accurately identify critical areas with accelerated lining wear, which was previously impossible using only averaged estimates.

5. 3. Lining wear prediction using machine learning

As part of our study, a predictive model of the lining erosion rate of a 6-jet tundish of a continuous billet casting machine for the conditions of PAT "ArcelorMittal Kryvyi Rih" was built. Based on statistical measurements, CFD modeling results and a large number of variables, the model was built using the Gradient Boosting Regressor (GBR) method – a modern regression machine learning algorithm capable of taking into account complex nonlinear dependences between input parameters. This approach provided high prediction accuracy ($R^2 > 0.99$) and allowed the model to be adapted to new operating conditions, which was confirmed by the results of validation on practical casting series. To demonstrate the adequacy of the model and compare it with actual data, the plot shown in Fig. 9 was constructed.

To predict the erosion rate of the refractory layer, the GBR gradient boosting model was used, which is an example of an ensemble machine learning method. This model does not have an analytical equation in the classical form, as in linear regression, since it consists of a set of successive decision trees that generally approximate the dependence of the target variable on a set of input features. The abscissa axis shows the actual values of the erosion rate, and the ordinate axis shows the values predicted by the GBR model. For ease of perception, a linear approximation of the model prediction results is performed, which makes it possible to assess the quality of approximation using the coefficient of determination R^2.

Although the GBR model does not have an explicit analytical equation due to its tree-like structure, its intermediate solutions can be interpreted at several levels. For example, the model is built as an ensemble of 500 trees of depth 3–5, which provides a generalized representation of the dependence of the lining wear rate on input parameters. One can view individual trees of the ensemble, for example, tree No. 100, the most influential parameters of which were: heat flux to the wall – 26% of the contribution; final casing temperature – 19%; shear stress in the near-wall zone – 13%; Ca, P concentrations and Mn/S ratio – together about 20%.

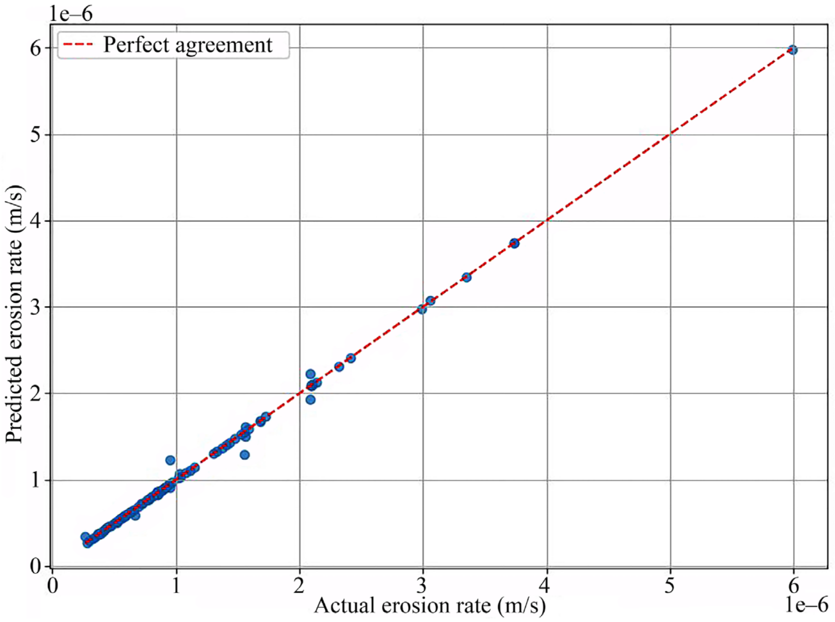

Fig. 9. Results of comparing the rate of refractory erosion in the tundish, obtained from actual data and calculation using a mathematical model

6. Discussion of results of modeling the heat and mass transfer process in the tundish of a continuous billet casting machine

Our modeling has made it possible to obtain spatial distributions of the hydrodynamic field, temperature, turbulent characteristics, and heat flows (Fig. 1–7), which became the basis for further determining the influence of these factors on the erosion rate of the lining. The results are explained by the influence of the geometry of the ladle, the metal level, the location of turbos tops, and pouring modes. Unlike typical approaches [2–4], our model takes into account the real structure of the lining and is tied to specific geometric characteristics, which makes it possible to localize areas with a high risk of overheating and stagnation zones with high spatial accuracy.

The frames shown in Fig. 8 depict a map of local wear, built taking into account mechanical, thermal, and chemical factors. Significant wear unevenness is explained by the combined effect of turbulence (Fig. 4–6), high temperatures (Fig. 3), and the content of aggressive elements (S, Si). Especially worth highlighting is the central zone of the ladle, directly under the place of the liquid steel jet, where critical wear areas are localized. It is here that turbulence, jet momentum, and high temperature values significantly affect the mechanical and thermal load on the lining. In addition, the primary mass of the melt with an increased content of non-metallic inclusions and aggressive elements is concentrated in this zone, which deepens chemical erosion. This distinguishes the proposed approach from conventional assessment methodologies that do not make it possible to spatially localize wear effects and take into account only averaged parameters.

In the zone of direct action of the jet, where the shear stress reaches 275 Pa, and the turbulent kinetic energy is 0.14 m^2/s^2, the erosion rate is 3.2–4.3 mm/h. For the opposite calm zones of the ladle (WSS about 88 Pa), the erosion rate decreases to 2.4 mm/h. An increase in temperature from 1791 K to 1830 K causes an increase in the erosion rate by 6–12%. When the carbon content changes from 0.03 to 0.18 wt. %, the erosion rate decreases by 0.8 mm/h. These dependences confirm the ability of the model to accurately describe local wear of the lining and substantiate practical recommendations for optimizing the steel composition and pouring modes.

The constructed multifactor model, based on a combination of CFD data and the chemical composition of steel, showed high accuracy ($R^2 = 0.99937$). The model effectively takes into account the complex influence of technological parameters, the chemical composition of the steel, and hydrodynamic characteristics. CFD parameters adapted to each plane and are key to forming an accurate erosion model. Machine learning methods, in particular a regression model with adaptation and validation, made it possible to achieve exceptional accuracy. The results could be integrated into digital modules for monitoring the condition of the tundish lining.

Our study eliminates the limitations of existing methodologies that did not make it possible to accurately localize overheating or erosion zones of the lining. Comprehensive CFD modeling taking into account real geometry and materials makes it possible to predict the service life of the lining and improve pouring modes.

It should be emphasized that our modeling did not take into account the deformation processes of the lining. Despite this, the accuracy of the model is high, and the result is practically applicable. In general, the model was built on the basis of practical data obtained as a result of measurements after 10 series of steel casting (about 30 control points). Subsequently, as new measurement data accumulated, the model was regularly supplemented and refined using machine learning methods. This ensured its ability to self-correct and adapt to changes in technological conditions, which was confirmed during application to new, previously unaccounted for, casting series. In the future, it is possible to use the model built and implement neural network architectures to detect nonlinear effects in the processes of lining erosion.

The disadvantages of our study are the unaccounted rheological properties of the lining and the dynamics of its damage over time. In the future, their elimination is possible by building a non-stationary multiphysics model taking into account phase transitions and damage accumulation.

7. Conclusions

1. A numerical model of heat and mass transfer in the tundish of a long-run CCM has been built using ANSYS CFX. The model takes into account the complex hydrodynamics of the melt, heat transfer through a multilayer lining, and erosion processes caused by mechanical, thermal, and chemical influences. The spatial distribution of temperature and velocity fields in the ladle volume and at the boundaries between the lining layers was determined. A quantitative assessment of the distribution of turbulent characteristics was carried

out: kinetic energy of the flow 9.7×10^{-4} to 1.6×10^{-3} m^2/s^2, dissipation – 2.5×10^{-3} to 5.4×10^{-3} m^2/s^3. That has made it possible to identify zones of increased erosion impact, where the erosion rate reaches 3.2–4.3 mm/h.

2. A map of local wear of the ladle lining has been constructed taking into account thermal, mechanical, and chemical effects. It was established that mechanical wear directly depends on the value of the near-wall shear stress, an increase of which by 100 Pa increases the erosion rate by 0.07 mm/h. The chemical aggressiveness of the melt is determined by the composition of the steel: an increase in the carbon content from 0.03 to 0.18 wt. % reduces the erosion rate by 0.8 mm/h. An increase in the steel temperature from 1791 to 1830 K increases the erosion rate by 6–12%. The greatest local wear is 3.2–4.3 mm/h, observed in the zone of contact of the liquid steel jet with the lining, where WSS reaches 275 Pa.

3. A predictive model of liner wear rate using machine learning methods has been developed. The model's feature is the ability to accurately predict local wear in specific areas of the liner, taking into account thermal, hydrodynamic, and chemical factors simultaneously. Unlike simplified empirical methodologies, our model demonstrated high accuracy ($R^2 = 0.99937$) and is able to adapt to changes in technological parameters in real time, which makes it possible to timely predict wear and optimize ladle maintenance schedules.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

References

1. Wang, Q., Tan, C., Huang, A., Yan, W., Gu, H., He, Z. et al. (2021). Numerical Simulation on Refractory Wear and Inclusion Formation in Continuous Casting Tundish. Metallurgical and Materials Transactions B, 52 (3), 1344–1356. https://doi.org/10.1007/s11663-021-02097-7
2. Wang, Q., Tan, C., Huang, A., Yan, W., Gu, H., He, Z. et al. (2021). Quantitative Characterization of Flow-Induced Erosion of Tundish Refractory Lining via Water Model Experiment and Numerical Simulation. Metallurgical and Materials Transactions B, 52 (5), 3265–3275. https://doi.org/10.1007/s11663-021-02254-y
3. Zhang, J., Qin, B., Liu, Y., Li, Q., Zuo, X., Wang, C. et al. (2023). Multiphase flow inside a four-strand continuous casting tundish using three types of ladle shrouds. Journal of Iron and Steel Research International, 30 (6), 1171–1181. https://doi.org/10.1007/s42243-023-00982-w
4. Dong, B., Lv, W., Xie, Z. (2024). Research on temperature prediction model of molten steel of tundish in continuous casting. Scientific Reports, 14 (1). https://doi.org/10.1038/s41598-024-78611-z
5. Box, G. E. P., Hunter, J. S., Hunter, W. G. (2005). Statistics for Experimenters: Design, Innovation, and Discovery. Wiley, 672.
6. Wang, T., Wang, J., Chen, C., Chen, L., Geng, M., Song, J. et al. (2024). Physical and Numerical Study on Right Side and Front Side Gas Blowing at Walls in a Single-Strand Tundish. Steel Research International, 95 (9). https://doi.org/10.1002/srin.202400037
7. Zhou, H., Li, H., Deng, X., Liu, B., Ji, C., Chen, B. et al. (2024). Optimization of Vortex Slag Entrainment during Ladle Teeming Process in the Continuous Casting of Automobile Outer Panel. Steel Research International, 95 (10). https://doi.org/10.1002/srin.202400322
8. Cramb, A. W. (Ed.) (2018). Making, Shaping and Treating of Steel: Continuous Casting. Pittsburgh: AIST.
9. Bathe, K.-J. (2006). Finite Element Procedures. Klaus-Jurgen Bathe, 1037.
10. Synehin, Ye. V., Sukhovetskyi, S. V. (2022). Analytical studies and characteristics of steel refining methods in the CCM tundish. Teoriia i praktyka metalurhii, 4, 25–29. Available at: https://crust.ust.edu.ua/items/d0c7753a-eb06-4b78-9df0-82f88c18f80b
11. Smirnov, O. M., Kuberskyi, S. V., Shtepan, Ye. V. (2011). Bezperervne rozlyvannia stali. Alchevsk: DonDTU, 518.
12. Sigarev, E. N., Chernyatevich, A. G., Chubina, E. A. (2007). Thermodynamic andgas-dynamic aspects of the guniting of converter linings. Steel in Translation, 37 (2), 92–98. https://doi.org/10.3103/s0967091207020039
13. Zovnishnia torhivlia Ukrainy tovaramy u 2021 rotsi (2022). Derzhavna sluzhba statystyky Ukrainy. Available at: https://www.ukrstat.gov.ua/express/expr2022/02/14.pdf
14. Vnesok HMK v ekonomiku Ukrainy 2024 (2025). GMK Center.Available at: https://gmk.center/wp-content/uploads/2025/04/ukr_2025_Econ_Steel-impact.pdf
15. Ruban, V., Stoianov, O., Niziaiev, K., Synehin, Y. (2021). Determining changes in the temperature field of a graphitized hollow electrode during metal processing periods in ladle-furnace. Eastern-European Journal of Enterprise Technologies, 2 (1 (110)), 109–115. https://doi.org/10.15587/1729-4061.2021.230002
16. Launder, B. E. (1972). Lectures in mathematical models of turbulence. London: Academic Press, 169.