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Mathematical model of the blast furnace main trough lining condition

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Abstract. The main trough of a blast furnace represents a complex technological structure that plays a critical role in the ironmaking process by draining molten cast iron and slag from the furnace hearth, thus ensuring the continuity and safety of the process. The reliable operation of the trough directly impacts the blast furnace productivity. The trough must be designed to withstand extremely high temperatures and aggressive chemical environments, and its proper functioning requires constant monitoring and maintenance. Selection of refractory materials and lining technology, as well as the potential for enhancing the resistance of refractory linings in the main mining troughs and extending their service life, are contingent on the timely acquisition of information regarding the thermal load on the refractory layers and casing, the operating conditions, design characteristics, and destruction processes of refractories in interaction with cast iron and slag. The control systems of the blast furnace main mining trough are designed to ensure its safe and efficient operation, by detecting deviations from normal mode in a timely manner and preventing emergency situations. These systems include visual, instrumental and automatic control. The monitoring system of the main mining troughs heat-up will allow the blast furnace technological personnel to control the condition of troughs, estimate their remaining life and make timely decisions on their repair. The developed mathematical model of the blast furnace main trough lining condition takes into account real-time thermocontrol of the blast furnace mining trough casings. It is aimed at obtaining operative information on the main mining troughs heat-up, and is based on the solution of the problem of stationary heat conduction of a multilayer flat wall, each layer of which is a homogeneous wall.

Keywords: blast furnace, main mining trough, mathematical modelling, thermocouple, heating, lining, temperature, control, algorithm, heat transfer

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Математическая модель состояния футеровки главного желоба доменной печи

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Аннотация. Главный горновой желоб доменной печи – это сложная технологическая конструкция, играющая критическую роль в процессе выплавки чугуна. Он служит для отвода расплавленного чугуна и шлака из горна печи, обеспечивая непрерывность и безопасность процесса. Надежная работа желоба напрямую влияет на производительность доменной печи. Конструкция желоба должна выдерживать экстремально высокие температуры и агрессивную химическую среду, а его правильное функционирование требует постоянного контроля и обслуживания. Корректный выбор огнеупорных материалов, технологии футерования, а также выявление возможности повышения стойкости огнеупорной футеровки главных горновых желобов и продления срока их службы определены своевременным получением информации о тепловой нагрузке на слои огнеупоров и кожух, об условиях эксплуатации, конструктивных особенностях и процессах разрушения огнеупоров при их взаимодействии с чугуном и шлаком. Системы контроля работы главного горнового желоба доменной печи призваны обеспечивать безопасную и эффективную его эксплуатацию, своевременно выявляя отклонения от нормального режима и предотвращая аварийные ситуации. Они включают в себя визуальный, инструментальный и автоматический контроль. Система мониторинга разгара главных горновых желобов позволит технологическому персоналу доменной печи контролировать состояние желобов, оценивать их остаточный ресурс и принимать своевременные решения об их ремонте. Разработанная математическая модель состояния футеровки главного желоба доменной печи учитывает термоконтроль кожухов горновых желобов в реальном времени. Она нацелена на получение оперативной информации по разгару главных горновых желобов и основана на решении задачи стационарной теплопроводности многослойной плоской стенки, каждый слой которой является однородной стенкой.

Ключевые слова: доменная печь, главный горновой желоб, математическое моделирование, термопара, разгар, футеровка, температура, контроль, алгоритм, теплопередача

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Introduction

The blast furnace runner system usually includes a main trough and pouring troughs, with the main trough serving as the location where molten cast iron is separated from slag. Consequently, it operates under the most severe conditions. For this reason, the improvement of its lining receives the greatest attention from both refractory manufacturers and end users.

Available research on heat transfer in the lining of the blast furnace main trough is far more limited compared to studies on the furnace's internal lining. However, in recent years, information from international publications has made it possible to assess the efforts made to study this issue.

In scientific studies addressing molten cast iron – slag separation in blast furnace main troughs, a wide range of methods has been employed, combining experimental and numerical approaches [1 – 3]. Experimental investigations, such as those reported in [4; 5], relied on physical modeling in which analog fluids (e.g., oil and water to simulate cast iron and slag) were used to examine the influence of trough geometry (inclination angle, cross sectional shape) and tapping velocity on phase separation efficiency. In [5], in particular, a 1:10 scale model was utilized to validate the results of numerical simulations.

Numerical modeling plays a central role in analyzing the complex heat and mass transfer processes in the trough [6 – 9]. Researchers have adopted different numerical approaches, including the finite volume method [7] and the finite element method [8 – 11]), solving the Navier–Stokes equations to describe flow hydrodynamics and the heat conduction equation (with allowance for radiation [11 – 13]) to simulate the temperature field. Key factors influencing separation efficiency and lining service life have been considered, such as flow turbulence [7; 9], heat transfer between the melt and the refractory [14 – 17], thermal radiation [10; 12; 13], and refractory wear [10]. For example, in [7] a k–ε turbulence model was applied, while in [10; 13] nonlocal boundary conditions were introduced to account for thermal radiation. In [8], the authors focused on identifying critical isotherms to extend lining service life, employing a two dimensional heat transfer model and comparing simulation results with experimental data. In [10], it was demonstrated that an adaptive time step regulator could be developed to improve the efficiency of long cycle blast furnace simulations.

In most cases, numerical modeling results showed good agreement with experimental data, making it possible to identify the regions of maximum temperature and stress in the lining [14 – 17] – most frequently in the sidewalls – and to predict its wear. Nevertheless, some uncertainties remain, particularly concerning the precise placement of thermocouples for temperature measurement in an operating trough [18 – 20], which necessitates the use of additional data processing techniques (e.g., the GRSA hybrid algorithm [10]) to refine the results. Overall, the combination of experimental and numerical methods has yielded a more comprehensive understanding of the complex processes occurring in blast furnace main troughs and has provided a foundation for developing recommendations to optimize their design and operation.

Input data

This study is devoted to the development of a mathematical model of the refractory lining of the blast furnace main trough, carried out at the Institute of Metallurgy of the Ural Branch of the Russian Academy of Sciences. An algorithm is presented for calculating the temperature field in the refractory lining of the trough based on thermocouple readings obtained from the outer surface of the trough's metal casing.

Fig. 1 shows a general (schematic) top view of two blast furnace main troughs.

The cross section of the refractory lining of the blast furnace main trough is shown in Fig. 2.

Calculation of heat conduction through a multilayer flat wall

The solution of this problem reduces to steady state heat conduction in a multilayer flat wall, each layer

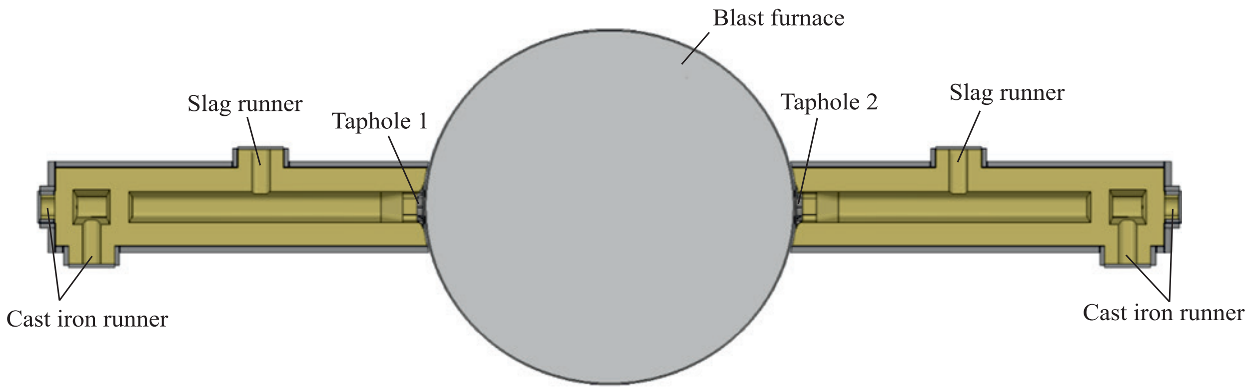

Fig. 1. Main mining troughs of the blast furnace

Рис. 1. Главные горновые желоба доменной печи

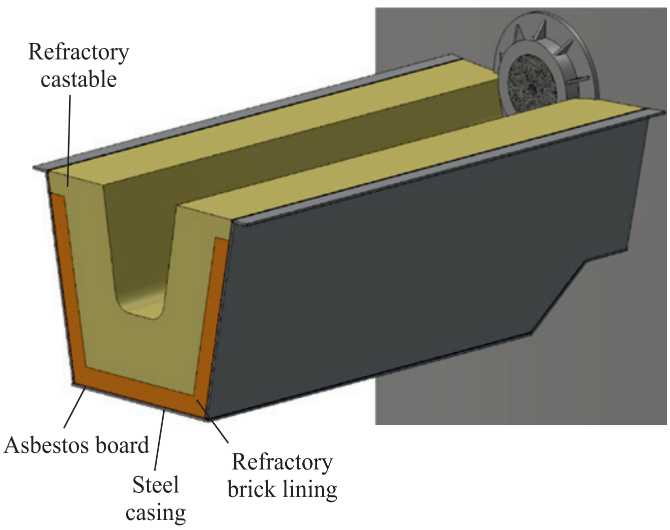

Fig. 2. Main trough lining layers in cross-section

Рис. 2. Слои футеровки главного желоба в поперечном сечении

of which is homogeneous. It is assumed that the total thickness of the multilayer wall, equal to the sum of the thicknesses of the individual layers, is much smaller than the wall's height and width. In this case, the isothermal surfaces are planes parallel to the boundary planes, including the planes of layer interfaces. The individual layers of the wall are assumed to have smooth boundary surfaces that fit tightly together, so that the temperatures of the contacting surfaces are equal (Fig. 3).

When considering heat conduction in a single layer wall, it is observed that the heat flux density does not change when moving from one isothermal surface to another along the x axis, i.e., from left to right.

The plane of the interface between the first and second layers likewise represents an isothermal surface with the same value of heat flux density as in the first layer. However, this plane serves as the "initial" surface for the second layer, in which a constant heat flux density q, equal to that in the first layer, is also established across the thickness δ_2. The same reasoning applies to all subsequent layers (δ_3, etc.).

The total heat flux, and hence its density, does not vary across the thickness of the multilayer flat wall ($Q \neq f(x)$ and $q \neq f(x)$). Therefore, for any i-th layer of the multilayer flat wall, the following relation holds

$$q_s = \frac{\Delta T_i}{\dfrac{\delta_i}{\lambda_i}} = \text{const}. \quad (1)$$

This relation can be expressed sequentially for all layers, beginning with the first:

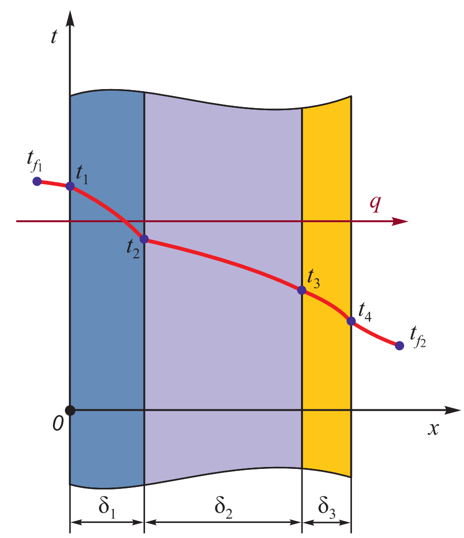

Fig. 3. Multilayer flat wall:
δ_1, δ_2, δ_3 – thickness of the first, second and third layers, respectively;
t_{f_1}, t_{f_2} – temperatures of hot and cold fluids, respectively;
t_1, t_4 – temperatures at the outer boundaries;
t_2, t_3 – temperatures at the plane of the layers interface

Рис. 3. Многослойная плоская стенка:
δ_1, δ_2, δ_3 – толщина первого, второго и третьего слоев соответственно; t_{f_1}, t_{f_2} – температуры горячего и холодного флюидов соответственно; t_1, t_4 – температуры на наружных границах; t_2, t_3 – температуры на плоскости раздела слоев

$$q_s = \frac{T_{f_1} - T_1}{\frac{1}{\alpha_1}} = \frac{T_1 - T_2}{\frac{\delta_1}{\lambda_1}} = \frac{T_2 - T_3}{\frac{\delta_2}{\lambda_2}} = \frac{T_3 - T_4}{\frac{\delta_3}{\lambda_3}} = \frac{T_4 - T_{f_2}}{\frac{1}{\alpha_2}}. \quad (2)$$

We then transform the obtained expressions into $q\frac{1}{\alpha_1} = T_{f_1} - T_2$ and sum them (combining left-hand sides with left-hand sides and right-hand sides with right-hand sides):

$$q\left(\frac{1}{\alpha_1} + \frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2} + \frac{\delta_3}{\lambda_3} + \frac{1}{\alpha_2}\right) = T_{f_1} - T_{f_2}.$$

These derivations remain valid for an arbitrary number of layers. Thus, in the general case, the expression for the surface heat flux density (q_s) is written as:

$$q_s = \frac{T_{f_1} - T_{f_2}}{\frac{1}{\alpha_1} + \sum_{i=1}^{n}\left(\frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_2}\right)}, \quad (3)$$

where α_1 and α_2 are the heat transfer coefficients from the hot fluid to the wall and from the wall to the cold fluid, respectively, W/(m^2·K); λ is the thermal conductivity of the material, W/(m·K).

Fig. 4 shows a scheme of heat transfer in the blast furnace main trough.

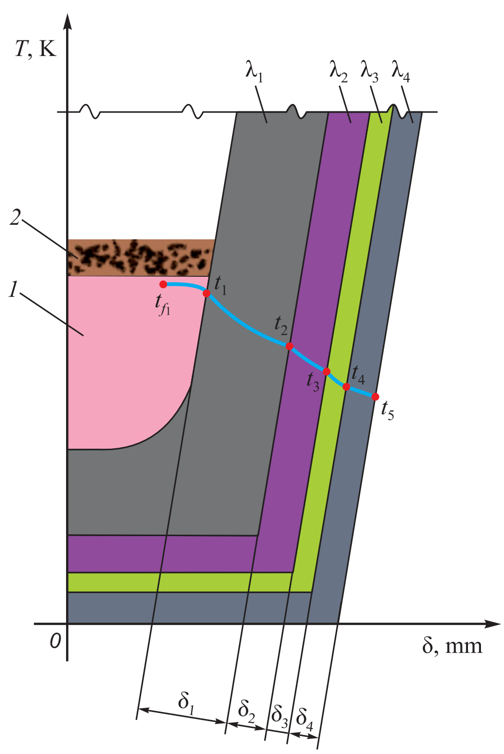

Fig. 4. Scheme of heat transfer of the main trough:
1 – cast iron; *2* – slag

Рис. 4. Схема теплопередачи главного желоба:
1 – чугун; *2* – шлак

Temperature monitoring is performed using thermocouples installed on the casing of the main trough. The lining of the main trough consists of three refractory layers and is enclosed by a steel casing; therefore, in this case, the expression for the surface heat flux density takes the form:

$$q_l = \frac{T_{f_1} - T_5}{\frac{1}{\alpha_1} + \frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2} + \frac{\delta_3}{\lambda_3} + \frac{\delta_4}{\lambda_4}}, \quad (4)$$

where T_{f_1} is the temperature of the hot fluid (cast iron, slag), K; T_5 is the casing temperature, measured by a thermocouple (heat removal can be recorded with a sampling interval from 10 s to 24 h), K; α_1 is the heat transfer coefficient from the hot fluid to the inner wall of the trough, W/(m^2·K); δ_1, δ_2, δ_3, δ_4 are the thicknesses of the refractory layers from the innermost to the outermost, m; λ_1, λ_2, λ_3, λ_4 are the thermal conductivities of the refractory materials from the innermost to the outermost, W/(m·K).

In the interfacial regions, the thermophysical properties of the materials are averaged.

Block diagram of the calculation algorithm

A block diagram of the algorithm for calculating the temperature variation across the lining layers is shown in Fig. 5.

Conclusions

The mathematical model developed for the blast furnace main trough lining, based on the solution of the steady state heat conduction problem in a multilayer wall, allows for an efficient evaluation of the thermal load on each refractory layer and the casing in real time (according to the configured heat removal sampling interval). This ensures continuous monitoring of the lining condition, enables prediction of its residual service life (specifically, the thickness of the inner layer), and supports timely decision making regarding repair or replacement. Such capabilities directly enhance the efficiency and safety of blast furnace operation, reduce the risk of emergency situations, and extend the service life of the lining. Future research will aim to further refine the model, for instance by incorporating transient thermal processes (introducing time dependence into the calculations) and by accounting for more complex geometric configurations of the trough.

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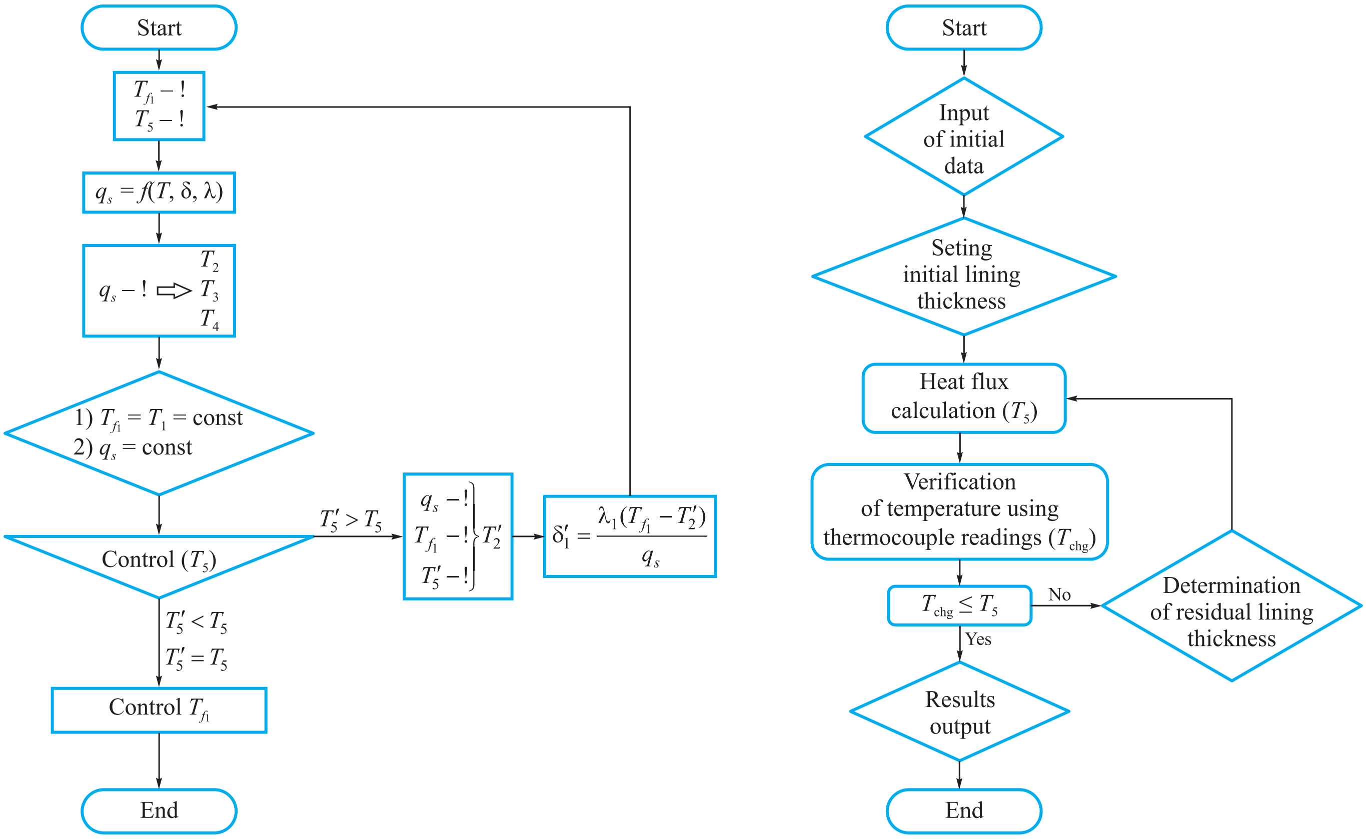

Fig. 5. Block diagram of the algorithm for calculation of temperature change by layers of the blast furnace main trough lining

Рис. 5. Блок-схема и диаграмма алгоритма расчета изменения температуры по слоям футеровки главного желоба доменной печи

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A. N. Dmitriev – formation of the article idea, scientific guidance, development of the research methodology, review and editing of the manuscript.
D. A. Vit'kin – performing calculations, analysis, data processing and discussion, writing the calculation algorithm, visualizing the results.

M. O. Zolotykh – writing the calculation algorithm.
G. Yu. Vit'kina – conceptualization, review preparation, text editing, data analysis and processing, writing the final manuscript.

Вклад авторов

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