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Оригинальная статья

Mathematical model of blast furnace hearth condition based on data from thermocouples in refrigerator belts

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Abstract. The control of blast furnace hearth lining is of critical importance in ensuring efficient and safe operation of blast furnace production process. Hearth lining plays a fundamental role in protecting the blast furnace walls from high temperatures and chemically aggressive slag melt. Early detection of high wear areas allows planning of preventive maintenance, thereby minimizing downtime and lost productivity. Furthermore, it contributes to the efficient use of resources by optimizing the replacement of damaged lining sections, thus avoiding unnecessary expenditure on preventive measures. The paper presents a three-dimensional unsteady model of blast furnace hearth, developed based on thermocouple data. This model facilitates estimation of the crucible heat-up and temperature distribution in the crucible masonry in three-dimensional and two-dimensional (graphical) forms. Estimation of the hearth lining burnout is achieved through the utilization of readings of the thermocouples installed in the hearth lining of blast furnace in the area encompassing the three lower refrigerator belts. Implementation of the mathematical model is permissible at any juncture following the overhaul of the first discharge. If a sufficient amount of time passed since the blast furnace was blown in, and there is a possibility of burnout or skull formation in the hearth lining, it is also necessary to utilize the results of ultrasonic control (USC) of the blast furnace lower part. The mathematical model of the blast furnace hearth condition enables informed decision-making by users regarding prevention of the emergency situations related to lining burnout, thus demonstrating its potential as a tool for enhancing the efficiency and safe operation of blast furnaces.

Keywords: blast furnace, hearth, mathematical modelling, thermocouple, heating, lining, control, heat transfer

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Математическая модель состояния горна доменной печи на основе показаний термопар, находящихся в поясах холодильников

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Аннотация. Контроль футеровки горна доменной печи является важным аспектом в обеспечении эффективной и безопасной работы доменного производства. Футеровка горна играет ключевую роль в защите стен доменной печи от воздействия высоких температур и химически агрессивного шлакового расплава. Раннее выявление зон повышенного износа позволяет планировать профилактические работы, минимизируя простои и потери производительности. Более того, это способствует эффективному расходованию ресурсов, так как позволяет оптимизировать замену поврежденных участков футеровки, избегая излишних затрат на превентивные меры. В работе приведено описание разработанной трехмерной нестационарной модели горна доменной печи, базирующейся на показаниях термопар. Модель позволяет оценить форму разгара горна и распределение температур в кладке горна в трехмерной и двумерной (графической) формах. Для оценки разгара футеровки горна использованы показания термопар, установленных в районе трех нижних поясов холодильников. Указанная математическая модель может быть внедрена в доменный процесс в любое время после капитального ремонта I разряда. В случае, если прошло достаточно много времени после задувки доменной печи и в футеровке горна возможно образование разгара или гарнисажа, необходимо также использовать результаты ультразвукового контроля нижней части доменной печи. Математическая модель состояния горна доменной печи позволяет принимать пользователю обоснованные решения по предотвращению аварийных ситуаций, связанных с прогаром футеровки, и является перспективным инструментом для повышения эффективности и безопасной эксплуатации доменных печей.

Ключевые слова: доменная печь, горн, математическое моделирование, термопара, разгар, футеровка, контроль, теплопередача

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Introduction

Effective control of hearth lining burnout in a blast furnace (BF) is an integral part of the comprehensive blast furnace process control system aimed at achieving high technical and economic performance.

There are several methods for monitoring hearth lining burnout in blast furnaces:

– application of systems analysis principles and solving direct and inverse problems of blast furnace heat performance control [1 – 3];

– systematic diagnostics of hearth lining condition using the reflected acoustic-ultrasonic signal (AU-E) method developed by the company [4];

– the method of group argument accounting, where the silicon content in hot metal is taken as the primary parameter for assessing the thermal state of the BF hearth [5];

– determination of the average heat flux of cooling water in the refrigerators [6; 7];

– analysis of the relationship between hearth lining design and lining wear [8 – 10].

One of the most reliable methods involves the installation of special thermocouples at specific points and in a defined number during a major overhaul. This subsequently allows for the monitoring of the thickness of the lining layers and assessment of the temperature gradient within the masonry [11 – 14]. The remaining thickness of the hearth and bottom lining, along with their two- and three-dimensional visualization, is calculated using both commercial software packages (e.g., Matlab [15]) and proprietary software solutions [16 – 18]. Among the available approaches, the finite element method is considered the most illustrative for modeling heat transfer [19; 20].

Monitoring the condition of the refractory hearth lining using a mathematical model [21] is feasible after the furnace blow-in and stabilization of its thermal regime. The mathematical model presented in this paper can be applied at any time after the overhaul of the first discharge category. If a significant amount of time has passed since the furnace was blown in, burnout or skull formation may occur in the hearth lining. In this case, it becomes necessary to use the results of ultrasonic control (USC) of the lower part of the blast furnace.

Input data

Fig. 1 shows a vertical section of the hearth of a 2000 m^3 blast furnace. It can be seen that the first refrigerator belt covers most of the bottom, while the second and third belts are located in the hearth crucible zone.

Thermocouples are installed in front of the three refrigerator belts in the hearth and bottom zones (20 thermocouples per belt). The data from these thermocouples, stored in the blast furnace automated process control system (APCS) database, can be used to assess hearth burnout. The data sampling interval may be as short as one minute. The concept of reference thermocouple temperatures (RTT) is introduced – these are the thermocouple readings taken at the moment of ultrasonic control (USC) for hearth burnout. The USC results provide information on the thickness of all refractory lining layers at four vertical levels. According to the results of the USC, wear of the ceramic blocks and carbon blocks, as well as the presence of skull formation, is observed in the hearth belt. The horizontal sections were taken at elevations of 6.5, 7.3, 7.9, and 9.9 m.

Fig. 2 presents a horizontal section of the hearth referenced to the tuyeres and tapholes. The origin of the cylindrical coordinate system is located at the center of the bottom at elevation 0. The zero-angle reference is aligned with the axis of tuyere *1* (Fig. 2), followed clockwise with equal angular intervals. In this system, the height remains constant and corresponds to the elevation of the slicing plane.

Thus, four slicing planes define the geometry of the skull formation. Using CAD software, a highly accurate 3D model of the hearth skull can be generated.

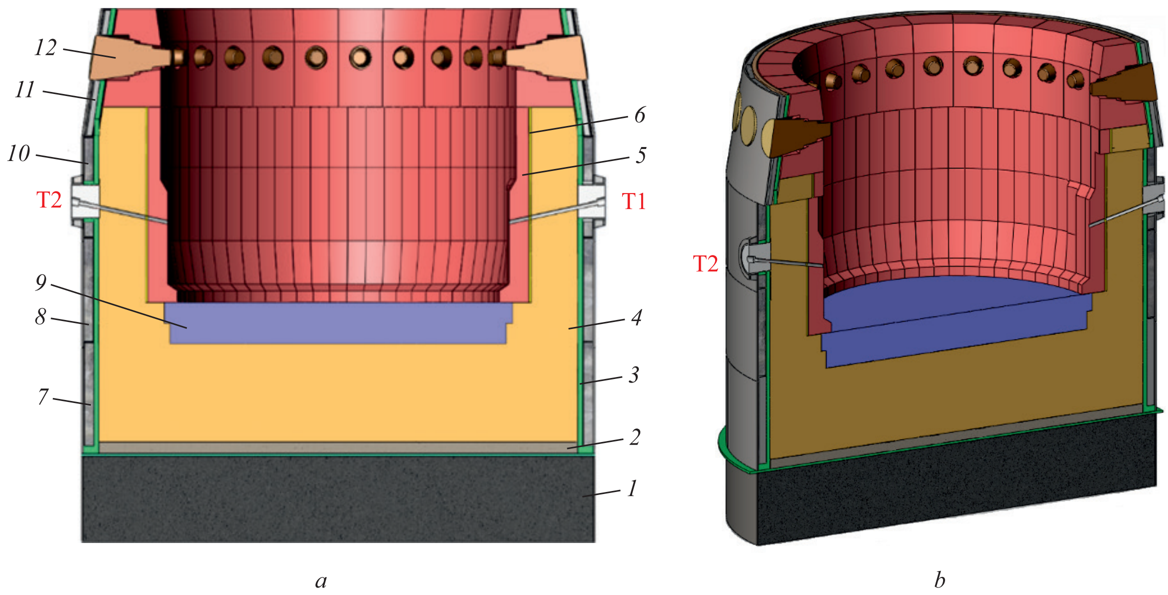


Fig. 1. Vertical section of the blast furnace hearth, including the bottom:
a – 2D-format; *b* – 3D-format:
1 – BF foundation; *2* – graphite blocks; *3* – refractory packing mass; *4* – carbon blocks of different density;
5 – ceramic cup; *6* – refractory insulating mass; *7* – refrigerators (1 belt); *8* – refrigerators (2 belt);
9 – ceramic layer of the bottom; *10* – refrigerators (3 belt); *11* – refrigerators (4 belt); *12* – tuyeres; T – taphole

Рис. 1. Вертикальный разрез горна доменной печи, включая лещадь:
2D-формат (*a*); 3D-формат (*b*):
1 – фундамент ДП; *2* – графитовые блоки; *3* – огнеупорная набивная масса; *4* – углеродистые блоки различной плотности;
5 – керамический стакан; *6* – огнеупорная изоляционная масса; *7* – холодильники (первый пояс);
8 – холодильники (второй пояс); *9* – керамический слой лещади; *10* – холодильники (третий пояс);
11 – холодильники (четвертый пояс); *12* – фурменные приборы; Т – летка

The computational domain includes the sidewall zone of the hearth and the bottom zone, where heat transfer is described by the heat conduction equation for solid materials. The initial conditions are the known data

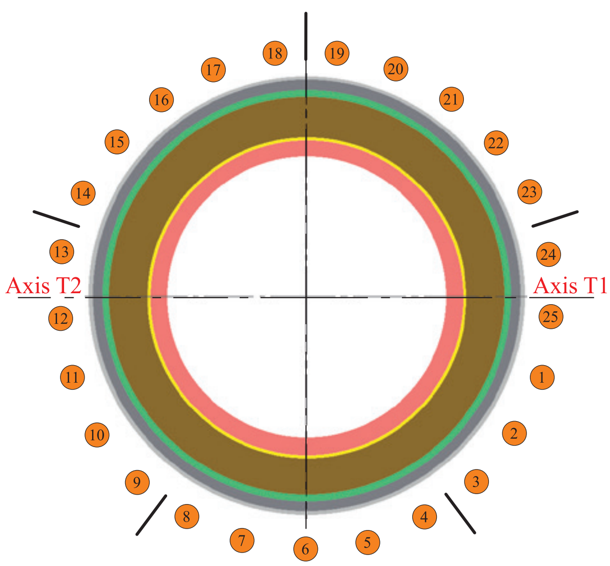


Fig. 2. Horizontal section of the furnace hearth with reference to 25 tuyeres and 2 tapholes

Рис. 2. Горизонтальный разрез горна с привязкой к 25 фурменным приборам и двум леткам

from the latest USC (reference temperatures). The internal boundary is the contact surface between the molten metal and the lining (skull). The temperature of the inner surface of the lining is assumed to be equal to the current temperature of the hot metal, measured by thermocouples installed in the blast furnace taphole. If such thermocouples are absent, the temperature is assigned by the operator (e.g., 1450 °C). The external boundary condition is defined by the thermocouple readings in the refrigerator belts. It is assumed that the temperature of the cooling agent in the refrigerators remains constant. For simplification, an ideal thermal contact between lining layers is assumed. In the interface zones, the thermophysical properties of the materials are averaged.

Heat transfer through a multilayer cylindrical wall

The linear heat flux density through a cylindrical wall was calculated using formulas (1) – (3)

$$q = \frac{\pi(T_1 - T_2)}{\frac{1}{\alpha_1 d_1} + \frac{1}{2\lambda}\ln\frac{d_2}{d_1} + \frac{1}{\alpha_2 d_2}} =$$

$$= k_l \pi (T_2 - T_1) = \frac{\pi(T_2 - T_1)}{R_1}; \qquad (1)$$

$$k_l = \frac{1}{\dfrac{1}{\alpha_1 d_1} + \dfrac{1}{2\lambda}\ln\dfrac{d_2}{d_1} + \dfrac{1}{\alpha_2 d_2}}; \quad (2)$$

$$R_1 = \frac{1}{\alpha_1 d_1} + \frac{1}{2\lambda}\ln\frac{d_2}{d_1} + \frac{1}{\alpha_2 d_2}, \quad (3)$$

where T_1 and T_2 are the temperatures of the hot and cold fluids, °C (K); 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, W/(m^2·K); d_1 and d_2 are the inner and outer diameters of the cylindrical wall, m; λ is the thermal conductivity of the wall material, W/(m·K); k_l is the linear heat transfer coefficient through the cylindrical wall, W/(m·K); R_1 is the linear thermal resistance of the cylindrical wall, (m·K)/W.

When heat is transferred through a cylindrical wall composed of *n* layers with different thicknesses and thermal properties, the linear heat flux density is calculated using the following formula (4)

$$q = \frac{\pi(T_1 - T_2)}{\dfrac{1}{\alpha_1 d_1} + \sum\limits_{i=1}^{n}\dfrac{1}{2\lambda_i}\ln\dfrac{d_{i+1}}{d_i} + \dfrac{1}{\alpha_2 d_{n+1}}}, \quad (4)$$

where λ_i is the thermal conductivity of the *i*-th layer, W/(m·K); d_i and d_{i+1} are the inner and outer diameters of the *i*-th layer, m.

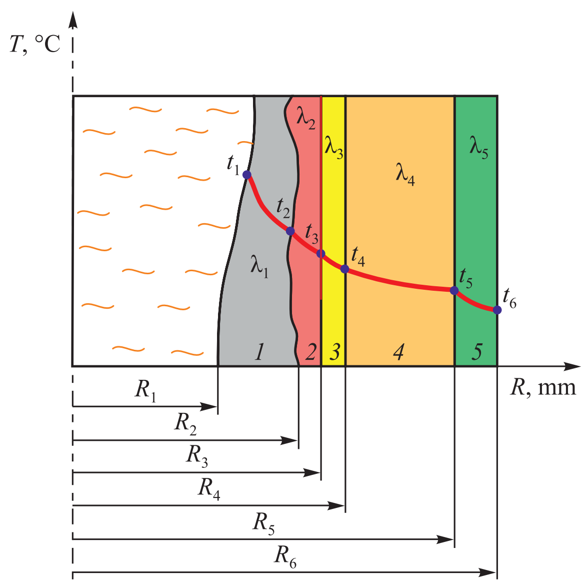


Fig. 3. Layers of insulating materials in the area of the second belt of refrigerators:
1 – skull; *2* – ceramic cup; *3* – refractory insulating mass;
4 – carbon blocks; *5* – refractory packing mass

Рис. 3. Слои изоляционных материалов в области второго пояса холодильников:
1 – гарнисаж; *2* – керамический стакан;
3 – огнеупорная изоляционная масса;
4 – углеродистые блоки; *5* – огнеупорная набивная масса

In this case, the linear thermal resistance of the wall is calculated as

$$R_l = \frac{1}{\alpha_1 d_1} + \sum_{i=1}^{n}\frac{1}{2\lambda_i}\ln\frac{d_{i+1}}{d_i} + \frac{1}{\alpha_2 d_{n+1}}. \quad (5)$$

Heat transfer through the five-layer wall was modeled at four specified heights, with known layer thicknesses (e.g., in the region covered by the second refrigerator belt, the layers are shown in Fig. 3).

Due to the degradation of the ceramic cup and insulating material, their actual thicknesses in the temperature control sector (TCS) differ from the design values. The height of the TCS corresponds to the height of the refrigerator. In each horizontal section along the TCS, the temperature of the refractory lining materials varies from point to point, resulting in different degrees of lining erosion (or skull thickness). Each TCS is subdivided into equal-height segments. For each sectional plane, the thickness of all refractory layers is determined, and the temperature distribution across the plane is calculated. Based on the known temperature, the behavior of each layer under increasing or decreasing overall temperature is proportionally estimated.

Let us consider the cross-section at a height of 6.5 m (Fig. 4). The thickness of the skull varies in the radial direction (from $S_{(2–4)}$ to $S_{(1–3)}$). The coordinates of points T_1 and T_2 shift depending on the following conditions:

– if the skull thickness increases, T_1 and T_2 move toward the center of the furnace, and the temperature in the sector decreases;

– if the skull thickness decreases, T_1 and T_2 shift toward T_3 and T_4, respectively, resulting in a temperature increase.

Based on the thermocouple temperatures recorded on the day of the ultrasonic control (USC), reference tem-

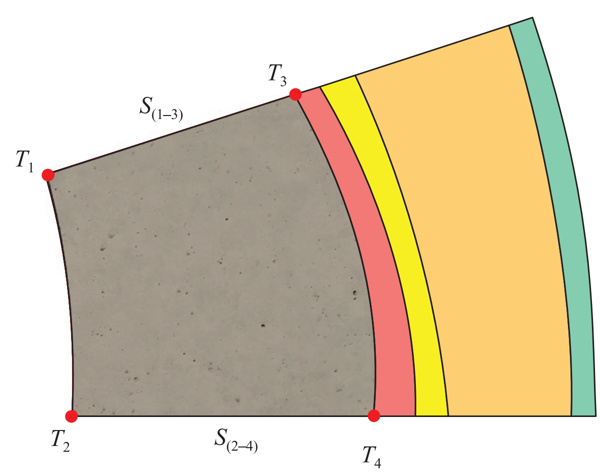


Fig. 4. Temperature control sector in the 6.5 m plane (bottom view)

Рис. 4. Сектор контроля температуры в плоскости 6,5 м (вид снизу)

Input data for calculation

Исходные данные для расчета

Insulating material	Thermal conductivity, W/(m·°C)	Layer thickness, mm
Skull	0.36	*X*
Ceramic cup	4.0	340*
Refractory insulating mass	4.0	60*
Super-microporous carbon blocks	17	1282*
Refractory packing mass	18	130
Microporous carbon blocks	11	1282*
Ceramic layer of the bottom	1.74	*Y*
Super-microporous carbon blocks of the bottom	17	650
Carbon blocks of the bottom	11	1950
Graphite blocks of the bottom	100	295
Refractory packing mass of the bottom	18	70
* Thickness before the formation of skull.		

perature distributions within the hearth masonry can be determined for all levels.

The thermal conductivity of the skull formation depends on various factors, including its density [22]. In the present calculations, the value of $\lambda_s = 0.36$ W/(m·°C) is assumed.

The Table above presents the input data used for the heat transfer calculations.

Heat conduction through a multilayer planar wall

The bottom of the analyzed blast furnace is composed of seven tightly bonded layers. In the area covered by the first refrigerator belt, the layers (from the inner to the outer surface) are arranged as follows: skull, ceramic layer, super-microporous carbon blocks, carbon blocks, graphite blocks, refractory packing mass, and an air-cooled zone at the bottom, where thermocouples are installed).

The first refrigerator belt is divided by 20 cylindrical cutting planes (Fig. 5, *a*). The boundary points of skull formation in two refrigerator belts are shown in Fig. 5, *b*.

Heat transfer through the planar wall is calculated using the surface heat flux density, which is related to the total heat flux by the equation $q = Q/F$, where F is the surface area of heat exchange.

For a wall composed of n layers, the formula for calculating heat transfer through the planar wall is given by

$$q = \frac{T_1 - T_2}{\frac{1}{\alpha_1} + \sum_{i=1}^{n} \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_2}}, \qquad (6)$$

where δ_i and λ_i are the thickness and thermal conductivity of the i-th layer of the wall, and R_t is the overall thermal resistance of the multilayer wall, (m²·K)/W.

Then

$$R_t = \frac{1}{\alpha_1} + \sum_{i=1}^{n} \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_2}; \qquad (7)$$

$$q = \frac{T_1 - T_2}{R_t} = \frac{\sum_{i=1}^{k} \Delta T_i}{\sum_{i=1}^{k} R_{ti}} = \text{const}, \qquad (8)$$

where ΔT_i is the temperature drop across the i-th heat transfer section, °C (K); R_{ti} is the thermal resistance

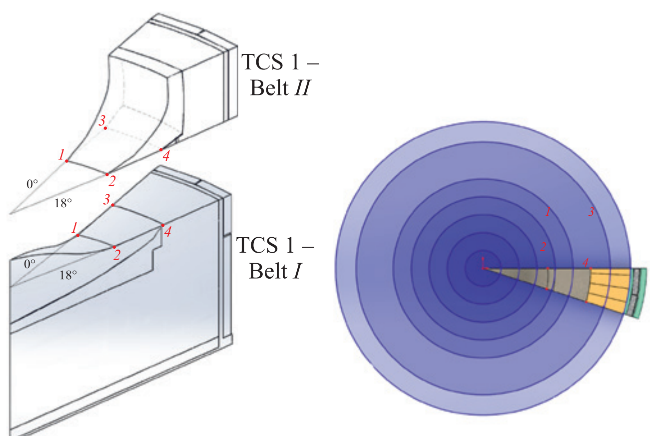
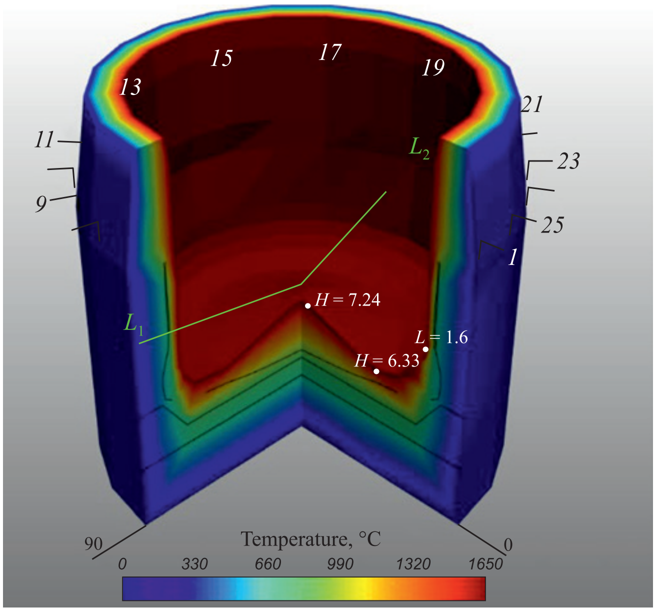
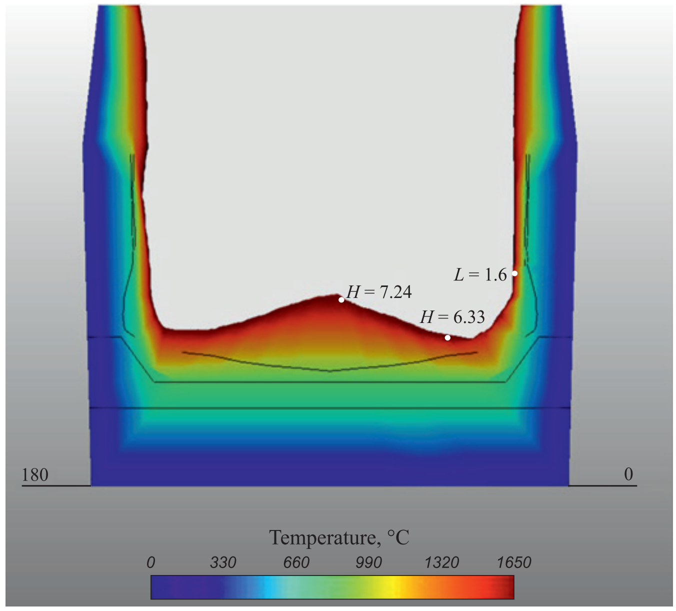


Fig. 5. Section by secant cylindrical planes (*a*) and boundary points of the skull of two belts (*b*)

Рис. 5. Сечение секущими цилиндрическими плоскостями (*a*) и граничные точки гарнисажа двух поясов (*b*)





a *b*

Fig. 6. 3D model of the hearth and bottom (temperature distribution) (*a*), two-dimensional section of the hearth and bottom model (*b*)

Рис. 6. 3D модель горна и лещади (температурное распределение) (*a*); двумерный разрез модели горна и лещади (*b*)

of the *i*-th heat transfer section, $(m^2 \cdot K)/W$; *k* is the number of heat transfer sections.

Visualization of the BF hearth and bottom

Two- and three-dimensional models of the blast furnace hearth are visualized using the Visualization Toolkit (VTK) – an open-source C++ library for modeling, image processing, and applied visualization.

Three-dimensional objects are defined by sets of vertices and faces connecting those vertices. Since these models represent quasi-solids of revolution, the vertex coordinates are specified in a cylindrical coordinate system. The origin of this system is located on an imaginary vertical axis passing through the center of the furnace, starting at elevation 0. However, VTK requires vertex coordinates to be provided in Cartesian coordinates X, Y, Z. Coordinate transformation is performed using the following formulas: $X = R\cos(A)$; $Y = R\sin(A)$; $Z = H$.

The coordinates of the vertices on the outer surface of the furnace are constant and defined at the model design stage. The inner surface vertex coordinates vary depending on the lining thickness calculated by the hearth burnout mathematical model. The color rendering of the masonry is displayed as a color gradient corresponding to the lining temperature (Fig. 6).

To enhance clarity in the 3D representation of the hearth, any sector can be cut out. This allows for visualization of the internal condition of the lining, with azimuthal section planes freely defined, enabling comprehensive inspection of the entire masonry volume. The cross-section ends are not generated directly by VTK during object slicing; instead, they represent a separate, specially calculated set of points. As a result, each visualization is constructed from four surfaces: the outer surface (constant), the inner surface (model-calculated), and two azimuthal cross-sections (model-calculated).

The accuracy of predicting the remaining thickness of the blast furnace hearth lining is determined by comparing the model results with the findings obtained from ultrasonic control (USC) inspections.

Conclusions

The application of the developed mathematical model enables optimization of the blast furnace smelting process by providing real-time control of the hearth and bottom lining thickness through visual representation. In turn, this opens the way to significant cost reduction through timely decision-making regarding process parameters.

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