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Heat Transfer in the Enclosing Structures of a Blast Furnace.
Part 1. Statement of the Problem and the Prerequisites for Calculation

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Abstract. Multilayer shielding structures of the blast furnace were examined. A description of the layers that are a part of these structures is presented. The lining layer is focused on. The process of cast iron smelting and the temperature zones of the individual layers of the blast furnace internal environment are briefly described. Based on A.V.Lykov’s theory original equations were analyzed, they describe interconnected heat and mass transfer in a solid object as applied to the given problem – appropriate process depiction aimed at the further rational development work on the multilayer shielding structures of the blast furnace. A priori the shielding mathematically is considered as an unlimited plate.

1. Introduction
Introductory №1 “Lining” according to [1] page 1437 – is “… a layer, coating from any refractory, chemically resistant or heat insulant material…”; according to [2] page 541 – is “… An internal defensive coating of thermal assemblies, furnaces, fireboxes, pipes, reservoirs, etc. Refractory, chemically resistant and heat insulant linings are distinguished.” according to [3] – is “… a special finishing to ensure surface protection from possible mechanical, thermal, physical and chemical damage…”. For our development work, we will highlight two keywords “Layer” and “Refractory”.

Introductory № 2 According to GOST R 52918-2008. Refractory materials. Terms and definitions. “Refractory material – nonmetallic material with fire resistance not less than 1580 degrees centigrade, used in assemblies and arrangement devices for protection from exposure to thermal energy and gas, liquid and solid corrosive reagents”. We will highlight “… material… for protection from exposure to thermal energy…”.

Introductory № 3. Linings, by universal practice, are implemented in the form of large-sized and shaped objects, the utilization of which is not recommended when significant thermal stresses are present. In this case, the usage of the lining layer out of ramming refractories and skull lining (with forced cooling) is recommended. Then in the lining layer (refractory), a liquid phase appears, which predetermines the transition into the plastic state and the fire resistance of the lining of the furnace increases.

Introductory № 4. “Skull or slag lining” according to [2] – “solid refractory protective layer that forms in the process of smelting on the internal working surface of walls of some metallurgical
assemblies and prevents them from wearing out. Appears as a result of the physicochemical interaction of the burden, gases and the material of the cooled walls”.

Introductory № 5. On fig. 1 is presented the scheme of a blast furnace and also the thermal effect on the lining layer of solid (fluxes, ore, combustible – preparatory zone), predominantly gas (restorative zone with loosened ore and ascending blast-furnace gases) and liquid (smelting zone) environment is illustrated.

Introductory № 6. On fig. 2 is presented the general case of the layered shielding of high temperature (blast) furnace with dummy cover.

Introductory № 7. On fig. 3 is presented the general case of the layered shielding of a blast furnace with forced cooling.

Summing up we obtain:

Lining layer, which as a first approximation for mathematical modeling can be presented as an unlimited plate (a similar approach is justified and examined in detail in [4,5]).

The internal environment of the blast furnace takes effect on the layer.

The wall of the furnace is a multilayered construction (see fig. 1, 2 and 3).

When assigning (calculating) the thickness of shielding structures of the blast furnace (lining layer, layer of thermal insulation, or cooling layer, air gap, cover layer and other layers) by universal practice, it is assumed that the process of heat transmission through the shielding is stationary. Therefore, its parameters correspond to the maximal furnace run-up (temperature regime) of the internal environment of the furnace when smelting cast iron [6]. However, all processes in nature are nonstationary.

Cast iron smelting cycle consists of approximately 60 hours (2.5 days) one day out of them is spent on warming up and half a day on cooling-down of the furnace. Thereby the relatively stationery (working) regime of heat transmission through shielding continues for a day.

The author’s goal is to examine the nonstationary influence of the parameters of the internal environment on the shielding structures of the blast furnace.

LIST OF SYMBOLS

t – temperature,
\( \tau \) – time,
\( \lambda_{q,m} \) – coefficients of heat and mass conductivity,
\( \alpha_m \) – coefficients of heat exchange and mass,
\( \Phi \) – thermogradient coefficient, referred to the difference of moisture content
r – specific heat of phase transition,
\( \varepsilon \) – phase transition criterion,
\( a_i = l_i/\epsilon g_0 \) – the coefficient of potential diffusivity of heat transmission (temperature conductivity),
\( l_q \) – the coefficient of heat conductivity,
c_q – specific thermal capacity,
\( g_0 \) – the density of the dry part of the object,
\( \nabla^2 \) – Laplace operator,
c_m – specific isothermal mass capacity,
\( \Theta \) – potential of matter transfer,
c_p – specific heat capacity at constant pressure,
t – time,
k – air permeability coefficient,
\( V \) – Hamilton operator,
\( \nabla \Theta \) – potential gradient of mass transfer,
\( VP \) – total pressure gradient,
\( \nabla t \) – temperature gradient,
\( a_m = \frac{L_m}{c_m g_0} \) - the coefficient of potential diffusivity,
\( l_m \) - the coefficient of mass conductivity,
\( P \) – filtration movement coefficient,
\( a_p = \frac{k}{(c_0 g_0)} \) - coefficient of potential diffusivity of filtration movement of steam,
\( c_s \) - coefficient of proportionality,
\( q_0 \) – density of the heat flow,
\( q_m \) – density of matter mass flow.

Index “ext” refers to the characteristics of the external environment, and index “int” to the characteristics of the internal environment,
\( F_{oq} = a_q \tau R^2 \) - Fourier number (heat exchange);
\( F_{om} = a_m \tau R^2 \) - Fourier number (mass exchange);
\( Lu = a_m q_0 \) – Lurie number – interconnection of mass and heat transfer (criterion of inertia);
\( Ko = r_0 \tau u/c_0 \gamma_0 \) - Kossovich number;
\( Ko* \) - modified Kossovich number;
\( Pn = \delta_0 \tau u/c_0 \) – Posnov number.

Other symbolic notations are given in the text according to the original source and additionally explained.

2. Methods

Let us examine the shielding presented on fig. 1; 2 and 3. Interconnected heat and mass transfer in the solid object (in our case in the lining layer) are described by a set of equations in partial derivatives in the form:

\[
\frac{\partial \Theta}{\partial \tau} = a_m \nabla^2 \Theta + a_m \delta \nabla^2 \tau + a_m \delta^2 \nabla^2 P
\]
\[
\frac{\partial P}{\partial \tau} = a_p \nabla^2 P - \frac{c_m}{c_0} \frac{\partial \Theta}{\partial \tau}
\]

Boundary conditions on the surface of the object take the form:

\[
-\lambda_q \nabla t + q_0 \tau - 1 - \varepsilon r_{q_m} \tau = 0
\]
\[
\lambda_m \nabla \Theta + \lambda_s \delta \nabla t + \lambda_p \nabla P + q_m \tau = 0
\]
\[
P_n = P = \text{const}
\]

Notice: herein (1)-(6) and later denominations are used that were cited in [7]. The influence of the effect of pressure diffusion for building constructions is small, that is why in engineering calculations it is often neglected, then the set (1)-(6) simplifies because the equations (3), condition (6) drop out and the third summand in the equation (5) turns to zero.

In the particular case when the influence of the thermal diffusion effect and internal phase transformations is negligibly small, and the main mass transfer is carried out through mass conductivity in equations (1) and (2) last summands of the right part of the equations disappear. The set of equations of interconnected heat-mass transfer splits into two independent problems of mass and heat transfer that are described by parabolic equations of heat transmission.

The first summand (4) \(-\lambda_q \nabla t\) represents the amount of heat, received from the surface into the object through thermal conductivity; the second summand \( q_0 \tau \) represents the amount of heat, brought to the surface of the object; the third summand \( 1 - \varepsilon r_{q_m} \tau \) represents the amount of heat, spent on liquid evaporation. If the evaporation takes place only inside the object \( \varepsilon = 1 \), then the third summand
turns to zero, physically only vapor is brought to the surface of the object. When \( q = 0 \) - only liquid is brought to the surface of the object, then the evaporation takes place only on the surface of the object. Equation (5) represents the matter mass balance equation. The physical meaning of it is that from the surface of the object the flow of moisture mass \( q_w \) is abstracted to the surroundings, but to the surface of the object, moisture is brought through potential gradient of mass transfer \( \lambda_w \), heat transfer \( \lambda_q \), and total pressure \( \lambda_p \). Equations (6) represents actual equality of pressure of gaseous mixture near the surface of the object and ambient barometric pressure.

For the given flow of heat \( q_q \) and moisture \( q_m \) boundary conditions (4) and (5) are boundary conditions of the second kind.

If we set the law of interaction of the object with the humid environment:
\[ q_q = \alpha_q \, \dot{t} - t_e \] - Newton Law;
\[ q_m = \alpha_m \, \Theta - \Theta_e \] - Dalton Law;
and substitute equations (8) and (9) into conditions (5) and (6), then we will receive boundary conditions of the third kind.

If the coefficients of heat exchange \( \alpha_q \) and mass exchange \( \alpha_m \to \infty \) or \( \lambda_q \) and \( \lambda_m \to 0 \), then out of the boundary conditions of the third kind one gets the boundary conditions of the first kind. Boundary conditions of the fourth kind represent ideal thermal and mass contact of the contacting surfaces:
\[ t_i = t_{i+1}, \quad \Theta_i = \Theta_{i+1}, \]
\[ -\lambda_q \nabla t = -\lambda_q \nabla \Theta \quad \nabla t_{i+1} = q_{m,i+1}. \]

Equations (9) represent the equality of potential of heat and mass transfer on the boundary of a joint between the \( i \) and \( i+1 \) layers, and equation (10) – the equality of flows a heat and moisture.

Equations of heat and mass transfer for a one-dimensional system are derived in [7] and appear as:
\[ \frac{\partial T}{\partial x} + \frac{\partial u}{\partial t} = 0; \]
\[ \frac{\partial u}{\partial t} = a_m \nabla^2 u + a_m \dot{t} \nabla^2 t. \]

In [7] based on the similarity theorem of Kirpichev-Guhman equations (11) and (12) are presented in the dimensionless variables and for the unlimited plate in designations of [7] appear as:
\[ \frac{\partial^2 T}{\partial x^2} = \frac{\partial^2 T}{\partial x^2} - K \nabla \Theta \nabla T; \]
\[ \frac{\partial^2 \Theta}{\partial x^2} = \frac{\partial^2 \Theta}{\partial x^2} - L \frac{\partial^2 T}{\partial x^2}. \]

In [7] a method for solving the differential equation system (13) and (14) with the use of Laplace transformation is proposed:
\[ F_L(x, s) = \int_0^s F(x, t) e^{-sT} \, dt. \]

Boundary conditions are also transformed into a dimensionless form.

First of all, let us examine the case presented on fig.1. For this example, the thermotechnical calculation will be dominant and not the moisture calculation. The presence of moisture in layers can be accounted for with the input of not a constant, but a variable value of coefficient thermal conductivity \( \lambda \) with account taken of all known patterns of relationship. Then the conversion from the set of equations (11, 12) to a classical Fourier equation of heat conductivity.
\[ \frac{\partial T}{\partial \tau} = a \frac{\partial^2 T}{\partial x^2}. \]
On the example of shielding presented on fig.1, we will simulate the problem of thermal transmission.

When physically-mathematically stating the problem of heat transmission with a nonstationary regime through multilayered shielding let us use the technique and designation used in [7].

We examine the shielding construction (see fig. 1). As a first approximation, we simulate a three-layer shielding: 1 layer – lining; 2 layer - thermal insulation; 3 layer – cover. On the left surface of layer 1 heat flow, q is applied. The right surface of layer 3 borders with the external (e) environment (e). The problem consists of determining the change of temperature t(x,τ) and heat flow q(x,τ) in time (τ) and in the space of thickness of the shielding (x). The accuracy of the thermotechnical calculation for building constructions depends on the choice of the right value of the thermophysical characteristics. In the computation usually two main determinants – coefficients of thermal conductivity (λ) and volumetric heat capacity (cρ). For the linear equation of heat conductivity when λ and cρ=const a coefficient of thermal diffusivity (a).

\[ a = \frac{\lambda}{c \rho} \]  \hspace{1cm} (17)

For the problem solution, it is necessary that the following are given: - starting conditions that determine the temperature distribution through the thickness and on the boundaries of the shielding at the zero time; the equations of heat conductivity that characterizes the conditions of the heat exchange on all the relevant planes. The starting conditions may be given as an equation, table or graph of temperature distribution at the initial moment of the process (when \( \tau = 0 \)). In the general case the starting conditions equations are of the form:

\[ T_{\text{start}} = t(x,0) \]  \hspace{1cm} (18)

The equation of heat conductivity in the general case is non-linear:

\[ \frac{\partial}{\partial \tau} \left[ \lambda(x,\tau) \rho(x,\tau) x,\tau \right] = \frac{\partial}{\partial x} \left[ \lambda(x,\tau) \frac{\partial t(x,\tau)}{\partial x} \right], \]  \hspace{1cm} (19)

Where the value of the coefficient of heat capacity \([c(x,\tau)\rho(x,\tau)]\) and the coefficient of heat conductivity \(\lambda(x,\tau)\) changes from one layer to another depending on the time, temperature and humidity. In our case, it is convenient to write down the system of linear differential equations with the constant coefficients. Each equation is written down for a separate layer \(i\) and \(c_i=\text{const}\) (\(i – \) the number of the layer):

\[ c_i \rho_i \frac{\partial t_i}{\partial \tau} = \lambda_i \frac{\partial^2 t_i}{\partial x^2}, \]  \hspace{1cm} (20)

On the boundary II (between the 1 and 2 layer) on the assumption of equality of heat flows and temperatures we will set the conditions of the fourth kind:

\[ \begin{align*}
\lambda_1 \left( \frac{\partial t_1}{\partial x} \right)_{II} &= \lambda_2 \left( \frac{\partial t_2}{\partial x} \right)_{II} & \text{or} & \quad q_1 = q_2 \\
t_1 |_{II} &= t_2 |_{II}
\end{align*} \]  \hspace{1cm} (21)

Analogously, we will write down the boundary conditions on boundary III.

Let us write down the boundary conditions of heat exchange on boundaries I and IV, i.e., on the internal and external surfaces of the shielding construction which is in contact with internal and external air and are also surrounded by other surfaces. The internal air has the temperature \(t_{\text{int}}\), external – \(t_{\text{ext}}\). If we account for the convection (convective exchange), then we introduce the coefficient \(c_{\text{conv}}\) into the calculation, if the radiant interchange, then the coefficient \(c_{\text{rad}}\) is introduced into the calculation. If a heat source is present then the amount of absorbed radiant heat by the surface I is determined like:

\[ q_{\text{in}} = p \cdot q. \]  \hspace{1cm} (22)
Where \( p \) – coefficient of absorption of the given radiation by the surface of the shielding (is assigned by tables in the relevant codes and standards, for example, СП 23-101-2004), \( q \) – the intensity of the incident radiation on the shielding.

If we examine the most common case, then on the surface of the shielding takes place a complex heat exchange, which is determined by the conditions of the second kind (given the intensity of the heat flow) and conditions of the third kind (given conditions of heat exchange with external environment). With the preceding in mind the boundary conditions on boundary I are of the form:

\[
\left. \alpha_{\text{int}} \left( t_{\text{int}} - t_{I} \right) \right|_{I} + \alpha_{\text{int}} \left( t_{R,\text{int}} - t_{I} \right) \right|_{I} + p_{\text{int}} q_{\text{int}} = -\lambda_{I} \frac{\partial t_{I}}{\partial x} \right|_{I} ;
\]  

(23)

where index (int) corresponds to the internal surface

Boundary conditions on the boundary 4 take the form of:

\[
\left. \alpha_{\text{ext}} \left( t_{I} - t_{4} \right) \right|_{4} + \alpha_{\text{ext}} \left( t_{R,\text{ext}} - t_{I} \right) \right|_{4} - t_{R,\text{ext}} + p_{\text{ext}} q_{\text{ext}} = -\lambda_{4} \frac{\partial t_{4}}{\partial x} \right|_{4} ;
\]  

(24)

For indoor spaces, the conditions of radiant-convective heat exchange in the building design practice are accounted for with a single coefficient of heat exchange \( \alpha_{\text{int}} \), then the condition (23) takes the form:

\[
\left. \alpha_{\text{int}} \left( t_{\text{int}} - t_{I} \right) \right|_{I} = -\lambda_{I} \frac{\partial t_{I}}{\partial x} \right|_{I} .
\]  

(25)

For workshop conditions under field observation and laboratory environment in the absence of heat sources in the laboratory (the absence of heating during the summer period) we can introduce an analogous simplification, and for the external surface of the examined shielding, then the condition (24) takes the form:

\[
\left. \alpha_{\text{ext}} \left( t_{I} - t_{4} \right) \right|_{4} = -\lambda_{4} \frac{\partial t_{4}}{\partial x} \right|_{4} .
\]  

(26)

For other cases instead of (24) one must use the condition that takes the form:

\[
\left. \alpha_{\text{ext}} \left( t_{I} - t_{4} \right) \right|_{4} = -\lambda_{4} \frac{\partial t_{4}}{\partial x} \right|_{4} ;
\]  

(27)

Condition (27) represents a composite boundary condition of the second and third kind. For convenience, condition (27) can be used with boundary conditions of the third type, introducing the conventional temperature of the external surroundings \( (t_{\text{conv}}) \):

\[
\left. \alpha_{\text{ext}} \left( t_{\text{conv}} - t_{4} \right) \right|_{4} = -\lambda_{4} \frac{\partial t_{4}}{\partial x} \right|_{4} ;
\]  

(28)

where \( t_{\text{conv}} = t_{\text{ext}} + p_{\text{ext}} q_{\text{ext}} / \alpha_{\text{ext}} \).

3. Results

Thus for our problem, out of its general formulation, we will choose for further research:

- starting conditions – equation (18) in the form of the graph of the temperature distribution within the thickness of the shielding;
- equation of heat conductivity (20);
- boundary conditions:
  - on the boundary I – condition (23)
- on the boundary II and III - condition (21)
- on the boundary IV - condition (24)

4. Conclusions
Solving the problem with the analytical approach causes severe mathematical difficulties, that is why in the following publications there will be purposed a mathematical model which will let us avoid them and adequately describe the process of nonstationary heat transfer in multi-layered structures. Besides that, the shielding present on fig. 2 and 3 will be examined.

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