Heat Transfer in the Enclosing Structures of a Blast Furnace.
Part 4. Examples of Calculation

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Abstract. The article is part of 4th cycle of articles under the general title "Heat transfer in the enclosing structures of a blast furnace". In Part 1, with the subheading "Statement of the problem and the prerequisites for calculation", typical multiwalled enveloping structures of a blast furnace are considered. The description of the layers in these structures is given. The main attention is paid to the lining layer. Briefly described the process of smelting cast iron and temperature conditions in the characteristic layers of the internal environment of the furnace. Based on the theory of A.V. Lykov, the initial equations describing the interconnected transfer of heat and mass in a solid are analyzed in relation to the problem posed (a proper description of the processes for the purpose of further rational design of the multilayered enclosing structure of the blast furnace). A priori enclosure from the mathematical point of view is considered as an unlimited plate. In Part 2 with the subtitle "Solving the boundary-value problems of heat transfer," the boundary-value problems of heat transfer in separate layers of the design with various boundary conditions are considered, and their solutions are given that are basic in the development of the mathematical model of the nonstationary heat transfer process in a multilayered enclosing structure. Part 3 presents a mathematical model of the process of heat transfer in the enclosure and an algorithm for its implementation. The proposed mathematical model allows to solve the following problems: - assess the thermophysical state of the designed structures under different operating conditions and, as a consequence, rationally design them for a particular mode or range of modes; - to calculate the temperature field in complex multi-layer constructions, for example, when the arrangement of the layers is discrete; - when temperature is measured at characteristic points (at the joints of layers and structural surfaces), it is possible to determine the thermophysical characteristics of the materials constituting the surveyed structure; - in laboratory tests it is possible to significantly shorten the test time, the researchers have the opportunity not to wait for the establishment of a regular regime; - it becomes possible to abandon the climate chamber and expensive instrumentation for experiments and research; - when solving the inverse problem, directly determine the resistance to heat transfer of the entire layered structure and its individual layers from the unsteady temperature field. Part 4 gives a number of examples of calculation of the heat transfer process in a multiwalled fencing of a blast furnace, which show the effectiveness of the proposed calculation procedure.
1. Introduction

Any mathematical model of the process must be adequate to its physical nature, and also take into account its specific features. The empirical approach to solving this or that problem, of course, has the right to life, but the merits of mathematical modeling in combination with experimental methods make it possible to create engineering methods for calculating various processes, and the common basis for the flow of heat and mass transfer processes in building materials makes it possible to draw a conclusion about the generality of their structural characteristics, to perform an analysis of the progress of a particular process in a concrete building material or structure and approximate the obtained results on adjacent materials taking into account their specific features. Here the commonality of the processes requires the unity of the approach to solving the problems of building thermophysics. The specific features of the simulated process cause the adjustment of the generalized mathematical description and its binding to a specific material or structure. Therefore, it is advisable to adhere to the following algorithm when calculating experimental studies and developing engineering calculation methods:

First of all, a competent, comprehensive and full-fledged formulation of the problem is needed (see Figure II.1, block 1), proceeding from this: the object of research, its characteristics (block 2); the physical process taking place in the object, and its features (block 3); mathematical description (model) of the object and the physical process (block 4). With further research, an analysis is made of the features of the object and the simulated physical process, identify the parameters (factors) that radically affect the course of the process. Then they analyze the mathematical model and identify the missing information for the implementation of this model (block 5). If the information for solving the system of equations in a closed form is sufficient, then the model realizes and receives the engineering calculation method (branch "YES" to block 6). If the information is not enough, then, as a rule, it can be obtained by experimental methods, for which a return is made to the object in order to carry out experimental studies and determine the missing parameters allowing to obtain a solution in a closed form (the "NO" branch to block 8). After that, they return to the mathematical model (blocks 4 and 5), develop the algorithm, flowchart and calculation program, that is, the engineering calculation method (block 6). Analyze the calculation methodology for its adequacy of object reflection (block 7). If the adequacy is satisfactory, then the task is considered solved (branch "YES" of block 7). If significant discrepancies between the experimental and calculated data are observed, then, in order to refine the calculation method, the way of solving the task can be passed anew or in part.

As an example, consider the enveloping structures of the blast furnace shown in Fig. 2 and 3.

Terms of tasks:
It is required to determine the temperature distribution along the thickness of the fencing structure of the blast furnace in the area of the zone of decomposition at the time of the first release of pig iron at the end of the blowing period (after a time, \( \tau = 24 \) hours), i.e. at the peak moment of heating of all layers of the enveloping structure of the blast furnace.

Initial data:
The unit is a blast furnace with a volume of 3300 m\(^3\).
Place of calculation – belly.

1 LAYER - lining - two-layer, thickness \( \delta_1 = 262 \) mm.
Type of used refractory - fireclay ШПД-41:
- density \( \gamma_1 = 1900 \) kg / m\(^3\);
- specific isochoric heat capacity \( C_1 = 287 \) J / (kg.C);
- coefficient of thermal conductivity \( \lambda_1 = 2.2 \) W / (m.C).

2 LAYER (рис.2) - mineral wool insulation (piercing mats):
- total thickness \( \delta_2 = 223 \) mm;
- density \( \gamma_1 = 840 \) kg / m\(^3\);
- specific isochoric heat capacity \( C_2 = 1122 \) J / (kg.C);
- coefficient of thermal conductivity \( \lambda_2 = 0.064 \) W / (m.C).
Figure 1.
2 LAYER (рис.2) - mineral wool insulation (piercing mats):
- total thickness $\delta_2 = 223$ mm;
- density $\gamma_1 = 840$ kg / m$^3$;
- specific isochoric heat capacity $C_2 = 1122$ J / (kg.C);
- coefficient of thermal conductivity $\lambda_2 = 0,064$ W / (m.C).

3 LAYER - casing - low-alloy steel, thickness $\delta_3 = 50$ mm.
- density $\gamma_3 = 7850$ kg / m$^3$;
- specific isochoric heat capacity $C_3 = 482$ J / (kg.C);
- coefficient of thermal conductivity $\lambda_3 = 58$ W / (m.C).

Internal environment parameters:
- temperature $t_{in} = 1000$оС;
- surface heat transfer coefficient $\alpha_{in} = 87$ W / (m$^2$.C).

Parameters of the external (external) environment:
- temperature $t_{ex} = 1000$оС;
- surface heat transfer coefficient $\alpha_{ex} = 23$ W / (m$^2$. ° C).

The results of the calculation for the task Fig.2:
Initial and boundary conditions.
Coefficient of heat exchange internal (W / (sq.m * deg. K)) = 87.00;
Internal temperature $t$ (deg. C) = 1000.00;
External heat exchange coefficient (W / (sq.m * deg. K)) = 23,00;
Outside temperature $t$ (deg. C) = 45.00;
The temperature of the layers is initial $t$ (deg. C) = 25.00;
Heating time (day) = 2;
Heating time (hours) = 0;
Heating time (minutes) = 0;
Heating time (seconds) = 0;
The thickness of the layer N1 (m) = 0.26;
The coefficient of thermal conductivity of the N1 layer (W / (m * deg. K)) = 0.06;
The density of the layer N1 (Kg / m3) = 1900,00;
The thickness of the layer N2 (m) = 0.22;
The coefficient of thermal conductivity of the N2 layer (W / (m * deg. K)) = 0.06;
The density of the layer N2 (Kg / m3) = 840.00;
The thickness of the layer N3 (m) = 0.05;
The coefficient of thermal conductivity of the N3 layer (W / (m * deg. K)) = 58.00;
The density of the N3 layer (Kg / m3) = 7850.00;
Boundary temperatures of the stationary process:
Left hand corner: 997,0002; 1-2 layers: 965,9200; 2-3 layers: 56.5719; Right hand corner: 56,3469;

Temperature distribution. 1st layer (step = 0.026200 m):
t (0.00) = 996.0109; t (0.03) = 991.8791; t (0.05) = 987.7515; t (0.08) = 983.6303; t (0.10) = 979.5176;
t (0.13) = 975.4155; t (0.16) = 971.3261; t (0.18) = 967.2514; t (0.21) = 963.1935; t (0.24) = 959.1544;
t (0.26) = 955.1359;

Temperature distribution. 2nd layer (step = 0.022300m):
t (0.00) = 955.1359; t (0.02) = 938.6749; t (0.04) = 925.4507; t (0.07) = 917.4369; t (0.09) = 916.1316;
t (0.11) = 912.4280; t (0.13) = 936.5419; t (0.16) = 258.0023; t (0.18) = 185.7018; t (0.20) = 117.9988;
t (0.22) = 52.8628;

Распределение температуры. 3-ий слой (шаг =0,00500м):
t(0,00)=52.8628; t(0,01)=52.8469; t(0,01)=52.8310; t(0,02)=52.8152; t(0,02)=52.7994;
t(0,03)=52.7838; t(0,03)=52.7682; t(0,04)=52.7526; t(0,04)=52.7372; t(0,05)=52.7218;
t(0.05)=52,7065.

Notes:
- the results were obtained both for stationary (steady-state) and for non-stationary heat transfer in the enveloping design of a blast furnace located in its widest part (dissipation);
- the initial data of the problem are taken from [17]. The results of the solution for the stationary process practically coincide, however, calculation by the proposed procedure allows us to consider the temperature distribution for nonstationary processes and at any time.

The results of the calculation for the task Fig.3:

Initial and boundary conditions.
Coefficient of heat exchange internal (W / (sq.m * deg. K)) = 87.00;
Internal temperature t (deg. C) = 1000.00;
External heat exchange coefficient (W / (sq.m * deg. K)) = 23.00;
Outside temperature t (deg. C) = 45.00;
The temperature of the layers is initial t (deg. C) = 25.00;
Heating time (day) = 2;
Heating time (hours) = 0;
Heating time (minutes) = 0;
Heating time (seconds) = 0;
The thickness of the layer N1 (m) = 0.26;
The coefficient of thermal conductivity of the N1 layer (W / (m * deg. K)) = 0.68;
The specific isochoric heat capacity of layer N1 (J / (kg * deg. K)) = 287.00;
The density of the layer N1 (Kg / m3) = 1900.00;
The thickness of the layer N2 (m) = 0.16;
The coefficient of thermal conductivity of the N2 layer (W / (m * deg. K)) = 0.68;
The specific isochoric heat capacity of layer N2 (J / (kg * deg. K)) = 4200.00;
The density of the layer N2 (Kg / m3) = 1000.00;
The thickness of the layer N3 (m) = 0.05;
The coefficient of thermal conductivity of the N3 layer (W / (m * deg. K)) = 58.00;
The specific isochoric heat capacity of N3 layer (J / (kg * deg. K)) = 482.00;
The density of the N3 layer (Kg / m3) = 7850.00.

Boundary temperatures of the stationary process:
Left hand corner: 973.2411; 1-2 layers: 695.9950; 2-3 layers: 148.2252; Right hand corner: 146.2183;

Temperature distribution. 1st layer (step = 0.026200 m):
| t (0.00) | 972.3016 |
| t (0.03) | 943.6057 |
| t (0.05) | 914.9169 |
| t (0.08) | 886.2388 |
| t (0.10) | 857.5750 |
| t (0.13) | 828.9289 |
| t (0.16) | 800.3041 |
| t (0.18) | 771.7039 |
| t (0.21) | 743.1314 |
| t (0.24) | 714.5900 |
| t (0.26) | 686.0825 |

Temperature distribution. 2nd layer (step = 0.016000 m):
| t (0.00) | 686.0825 |
| t (0.02) | 629.9357 |
| t (0.03) | 574.2141 |
| t (0.05) | 518.8969 |
| t (0.08) | 464.0209 |
| t (0.10) | 409.5895 |
| t (0.11) | 355.5906 |
| t (0.13) | 301.9975 |
| t (0.16) | 248.7692 |
| t (0.18) | 195.8522 |
| t (0.21) | 143.1822 |

Temperature distribution. 3rd layer (step = 0.005000m):
| t (0.00) | 143.1822 |
| t (0.01) | 142.9896 |
| t (0.02) | 142.7973 |
| t (0.02) | 142.6051 |
| t (0.03) | 142.2212 |
| t (0.03) | 142.0295 |
| t (0.04) | 141.8381 |
| t (0.04) | 141.6467 |
| t (0.05) | 141.4556 |
| t (0.05) | 141.2647 |

If the thickness of the cooling layer is increased to 320 mm, then boundary temperatures of the stationary process:
Left hand corner: 982.9949; 1-2 layers: 806.8069; 2-3 layers: 110.5989; Right hand corner: 109.3236.

If the thickness of the cooling layer is increased to 480 mm, then boundary temperatures of the stationary process:
Left hand corner: 987.0957; 1-2 layers: 853.3499; 2-3 layers: 60.9162; Right hand corner: 59.9484.
If the thickness of the cooling layer is increased to 640 mm, then boundary temperatures of the stationary process:
Left hand corner: 989.8689; 1-2 layers: 884.9019; 2-3 layers: 55.3466; Right hand corner: 54.5867.
For clarity, the results are summarized in Table 1.

| Thickness, mm | Left border | Joint of 1-2 layers | Joint of 2-3 layers | Right border |
|---------------|-------------|---------------------|--------------------|--------------|
| 160           | 973.2       | 696.0               | 148.2              | 146.2        |
| 320           | 983.0       | 806.8               | 110.6              | 109.3        |
| 480           | 987.1       | 853.4               | 60.9               | 59.9         |
| 640           | 989.8       | 884.9               | 55.3               | 54.6         |

Analysis of the data in the table allows us to draw the following conclusions:
1. The thicker (more powerful) the cooling layer:
   - the more evenly the lining warms up (layer 2);
   - less temperature stresses in the material of the lining layer, caused by uneven heating, and this increases the service life of the lining;
   - less heat loss;
   - the temperature on the outer surface of the casing (layer 3) is lower, which corresponds to the sanitary norms and excludes the appearance of traumatic injuries among the maintenance personnel;

2. Economic analysis was not carried out by the authors, however, it seems expedient to increase the one-time costs for the device of the refrigerator (layer 2), and thereby reduce the operating costs associated with the repair of the lining layer.

2. Results
The obtained results are correlated with the results obtained by other authors - this allows us to conclude that the new proposed mathematical model allows solving the problems of rational design of the enclosing structure, as well as simulating situations that arise at any time interval of fence operation.

Figure 2. - lining layer
Figure 3. - heat insulant layer 3 - cover
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