Heat Transfer in the Enclosing Structures of a Blast Furnace.
Part 3. Mathematical Model of the Heat Transfer Process

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Abstract. The article is part of 3rd 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.

1. Methods
The calculation of the temperature fields in a multilayer structure using analytical solutions (9), (23) and (32) [1] and their conjugations on each time interval is carried out as follows. At the initial time, the temperature of the enclosing structure has a uniform distribution and is equal to $t_0$ (Fig. 1a). From equation (9) the temperature field in the first layer of the structure for the first small time interval is calculated (Fig. 1b). Further, the value of the temperature gradient at the boundary of layers II and 2 is determined from expression (33). If the temperature gradient ($T_1$) is zero, the temperature field in the first layer for the next time interval is calculated (Fig. 1c) according to expression (9). If the temperature gradient ($T_1$) is nonzero its value is set as the boundary condition of the second kind (17) in task 2. In this case, the magnitude of the heat flux ($q_2$) and the Kirpichev's criterion ($K_i$) are...
determined by multiplying the temperature gradient (Γ1) by the thermal conductivity of the first layer (λ1). The temperature field in the second layer is calculated from expression (23) (Fig. 1e). The obtained new value of the temperature of the second layer at the contact point of layers 1 and 2 is given as the boundary condition of the first kind (3) in a task 1. With the new value of boundary condition (3) of a task 1, the temperature field in the first layer is estimated for the next time interval and continue this process until the moment when the gradient (Γ2) determined by the expression (34) becomes different from zero (Fig. 1e). The value of the nonzero gradient (Γ2) is set as the boundary condition of the second kind (26) in a task 3. In this case, the value of the heat flux (q3) and the criterion Ki are determined by multiplying the value of the temperature gradient (Γ2) by the coefficient of thermal conductivity of the second layer (λ2). The temperature field in the third layer is calculated from expression (32) (Fig. 1f). The obtained new value of the temperature of the third layer on the boundary III at the contact point of layers 2 and 3 is given as the boundary condition of the first kind (18) in a task 2. With the new value of the boundary condition of the first kind (18) in a task 2, the temperature field in the second layer is calculated (Fig. 1i). The obtained new value of the temperature of the second layer at the contact point of layers 1 and 2 is given as the boundary condition of the first kind (3) in a task 1. With the new value of the boundary condition (3) of a task 1, the temperature field in the first layer for the next time interval is calculated (Fig. 5k), and so on, until the gradient (Γ3) determined by expression (35) is different from zero (Fig. 1). Then by the method of successive approximations when t₃=tₙ the moment is calculated, and after depending on the task all the parameters of the multilayered enclosing structure are finally calculated. The algorithm is developed for a three-layer construction. In tasks 1 and 3, the outer (outer) layers are considered, in the task 2 - the middle layer. It is not difficult to extend this algorithm to an n-layer construction, because the last ones in the n-layer construction are the layers described in tasks 1 and 3, and each intermediate (middle) layer is described in task 2. Complicated only the flowchart (see Appendix 1) and the calculation program. With the appearance of 4, 5, 6 ... n layers between the block 2 of the program describing the middle layer and the block 3 describing the outer layer, the necessary (n-3) number of blocks of blocks 2 of similar structure are inserted in the structure under consideration.

It has been theoretically and experimentally proved that the entire heat exchange process can be divided into three stages [11].

Stage 1. Irregular mode. The thermal regime is disordered and strongly depends on the initial temperature distribution. At stage 1, it is necessary to investigate the series (9), (23) and (32) for small values of F₀, but this stage most closely describes the real conditions of heat transfer through the fence, for example, fluctuations in external temperatures, start and stop of the furnace, seasonal operation modes and etc.

Stage 2. Regular mode. The change in temperature is described by the first term in the series of expressions (9), (23) and (32) and is independent of the initial temperature distribution. The methods of stage 2 are called methods of a regular thermal regime, they are incorporated in the methodology of heat engineering calculation of all regulatory documents in force in the territory of the Russian Federation.

Stage 3. The temperature of all points of the body is the same and equal to the ambient temperature. From the theoretical point of view, one of the aspects of the analysis of solutions of the form (9), (23) and (32) is the determination of the time and sequence of the onset of the regular (working) thermal regime, the time factor is essential in solving many heat transfer problems.

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;
- calculate the temperature field in complex multi-layer constructions, for example, when the arrangement of 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.

The reliability criteria of the developed calculation methodology are:
- the identity of the solutions obtained by the SP technique and the proposed procedure for \( \tau = \infty \);
- deviation of calculated data from experimental data does not exceed 14%;
- approbation of the technique in full-scale studies of a multilayer structure (the enveloping design of a blast furnace) with subsequent opening of those places of construction in which the technique showed the absence of a heater or a decrease in its thermal properties and, as a result, overheating of the housing and unjustified heat loss.

2. Results
The proposed calculation methodology is implemented on a personal IBM-type computer and allows modeling of the temperature field distribution in the thickness of the enclosing structure over time. A block diagram of the calculation program and some examples of the results of calculating unsteady temperature fields in the body in multilayer structures are given in Part 4 of this work.

The presentation of the results of the account in digital and graphical form, as well as the possibility of varying the various parameters of the problem, allow simulating practically any situation and conducting its comprehensive analysis. The reliability of the results depends on the adequacy of mathematical modeling of the kinetics of processes.

All of the above allows us to recommend the developed mathematical model of heat transfer in a multilayered enclosing structure to practical application.

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Figure 1.