SCIENCE FOR CERAMIC PRODUCTION

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CONTROL OF THE TEMPERATURE CONDITIONS
OF FIRING IN FURNACES WITH RADIATING WALLS

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The possibility of achieving optimum conditions of heat treatment of ceramic articles in furnaces with radiating walls is shown. A function providing control of the thermal energy supply to the firing zone of the furnace is found for the considered example of solid brick firing in the furnace, which makes it possible to obtain high-quality articles at minimum intensity of heat transfer and minimum power consumption.

The problems of development of optimum conditions for heat treatment of ceramic products in firing furnaces are important due to the high power consumption and high cost of energy and fuel resources. The analysis of furnaces for wall ceramics firing in which the heat transfer from the furnace walls to the products is mostly implemented by radiation, revealed the existence of considerable reserves for energy saving [1]. The excessive power consumption in firing furnaces is above all related to the absence of methodology for determining the optimum conditions for heat treatment of ceramic articles, which only lately began to be elaborated [2].

The purpose of the present study is to show the possibility for developing optimum firing conditions for ceramic articles and controlling these conditions in furnaces with radiating walls. Due to the great variety of such furnaces, we restrict ourselves to considering the tunnel furnace described in [1] (a similar furnace currently operates in Kurtamysh, the Kurgan Region). The furnace is used to fire solid bricks made of Naumovskoe clay (Tomskii District) whose thermophysical properties were experimentally determined and described in [3]. The furnace output is 2.8 million bricks per year. The length of the preparation zone is 10 m, the length of the firing zone is 10 m, and the length of the cooling zone is 10 m. A charge placed on a firing car has a height of 1.56 m and a size 1.9 x 0.56 m in plane and consists of 704 bricks. The maximum heat flow density on the radiating wall in the firing zone can attain 16 kW/m². The firing duration is 30 h. The clearance between the vertically placed bricks in the charge was taken to be 66 mm, based on the recommendations given in [4].

The calculation of the temperature conditions for the firing furnace was carried out in accordance with the statement of the problem described in [1]. The values of convective heat transfer from the furnace walls and the products to the gases were found from the known similarity equations. It is assumed that free convection is absent in the channels between the articles in the firing zone, and the heat transfer in them is implemented only by radiation. For the analysis of the firing zone, the charge is considered as a flat parallelepiped consisting of a large number of elementary cells. The sizes of the articles (Fig. 1) are $l = 260$ mm, $25 = 67$ mm, $2S = 124$ mm. The other initial data in the numerical calculations of the heat problem were taken as follows: charge density — 0.677; distance from the radiating wall surface to the frontal surface of the articles in the charge — 0.05 m; area of the radiating wall surface of a cell — 0.0254 m²; frontal area of the surface of the articles in the charge — 0.0172 m²; radiating capacity of the furnace walls surface — 0.75, and of the articles — 0.57; thermal massive-ness of the furnace brickwork — 9200 kJ/K; firing temperature — 1123 K. The thermophysical properties of Naumovskoe clay are described by piecewise linear functions.

Analysis of the results of calculation of the ceramic charge heating showed that the maximum temperature drop for the entire cycle of heating, firing, and cooling of the articles is observed along the axis of the product, i.e., along the main direction of heat transfer. In this context, we considered a simplified setting of the optimization problem as a one-dimensional problem. The solution of the optimization prob-

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Fig. 1. Temperature drops arising along the article axis ($Y = Z = 0$) between the $X = 0$ and $X = 0.1$ sections depending on the heat flow density on the radiating wall: $X = x/l; Y = y/S; Z = z/L$. 1, 2, 3, 4, and 5) heat flow density $q_k$ for 8, 10, 12, 14, and 16 kW, respectively.

The first summand in the functional (2) takes into account the consumption of power in the heat treatment of the articles in $n$ charges. The second summand determines the inexactness of heating for the temperature field of the charge of articles at the end of the firing process. The third summand shows a deviation in the thermal stress on the surface of the body $\sigma_z$ from the prescribed value or the value required by the technology standards (the "perfect" value) $\sigma_p$.

The considered thermal and optimization problems are subjected to the following restrictions:

- a temperature of the article surface
  $T_s(\tau) \leq T_{s,\text{max}}$;

- a temperature of the radiating wall surface
  $T_k(\tau) \leq T_{k,\text{max}}$;

- a thermal stress
  $\sigma_p(\tau) \leq \sigma_{p,\text{max}}(\tau)$,

where $\sigma_{p,\text{max}}(\tau)$ is the permissible value of thermal stress in an article.

In order to determine the optimum controlling effect, the variation calculation using the Lagrange method of indefinite multipliers was applied [6]. For this purpose, the variation problem was reduced to a boundary problem and written in variations. The variation was determined from the relationship

$$\delta J = \int_0^1 \left[ \frac{2P_V(\tau)}{Mn} - \Psi_0(\tau)(a_3 - a_4 T_k) \right] \delta V d\tau,$$

where $\Psi_0$ is a Lagrange multiplier of first order determined from the obtained conjugated equation system.