Journal of Engineering Physics and Thermophysics, Vol. 75, No. 3, 2002

SOLUTION OF THE PROBLEM OF IDENTIFICATION OF THE PROCESS OF HEATING OF CYLINDRICALLY SHAPED BODIES IN INDUSTRIAL FURNACES

V. B. Kovalevskii, I. A. Koval'kova, and A. T. Koval'kov

UDC 621.785:681.3

The values of the coefficients of heat exchange by convection and radiation in the case of heating of cylindrically shaped billets in industrial furnaces are determined. The algorithm and the composition of software for the problem under solution are described. The results of testing and recommendations on assignment of the errors of computations of the coordinates of a minimum from the viewpoint of decrease in the calculation time are given.

Prediction of the process of heating in industrial furnaces and of the distribution of a temperature field in billets requires that the values of the coefficients of heat exchange by convection and radiation be known. This problem for billets of a rectangular cross section has been solved in [1] by identifying the mathematical model of heating on the basis of comparison of a theoretical model, which describes the process of heating, and experimental investigations, i.e., we selected such values of the coefficients of heat exchange by convection and radiation when the values of the temperatures of metal in a furnace (obtained as the solution of the equation of the process of heating) differed to the least degree from the same quantities but obtained experimentally. The values of the temperature were calculated at different points of the cross section from the surface to the center of a billet.

In the present work, we solve the analogous problem for cylindrically shaped billets; the temperature in the process of heating is calculated just on the billet surface according to the procedure of [2]. As a result of the calculations, we determine the values of the Stark (Sk) and Biot (Bi) similarity numbers, based on which one can determine the coefficients of heat exchange by convection α and radiation σ for the heating furnace under study.

The enlarged algorithm of operation of the basic program using modules is as follows:

1. Input of the initial data: the initial relative temperature of a billet, the relative time of heating, the axial step of the relative time, the values of the relative coefficients of thermal conductivity and heat capacity of the material, the coordinates of the points of the experimental curve of heating, the dimension of the function, the admissible error ε of determination of the coordinates of a minimum, the admissible error ε_1 of determination of the minimum of a one-dimensional function by the golden-section method, the lower and upper limits of variation, and the initial approximation of the Stark and Biot similarity numbers.
2. Approximation of the experimental curve of heating by a cubic spline [3].
3. Minimization of the objective function by the method of coordinate descent [3]; the minimum of the one-dimensional function is computed by the golden-section method.
4. Derivation of the calculation results: the value of the objective function at the point of minimum, the coordinates of this point (values of the Stark and Biot similarity numbers), the number of iterations, and the calculation time.

In calculating the temperature on the billet surface in accordance with the procedure of [2], the process of heating is subdivided into two successive stages: the inertial stage where the cylinder is only warmed up (the temperature of the center is still constant) and the regular stage where the temperature changes over the entire cross section now. At the latter stage, the temperature on the billet surface is determined by solving a rather cumbersome transcendental equation by the method of half-division.

The objective function has the form

Belarusian State Polytechnic Academy, Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 75, No. 3, pp. 100–101, May–June, 2002. Original article submitted December 6, 2001.

$$\delta = \int_0^{\mathrm{Fo_h}} \sum_{i=1}^{k} (\Theta_i - \Theta_{\mathrm{e}i})^2 \, d\,\mathrm{Fo}\,, \quad \mathrm{Fo} = at/R^2\,, \quad \Theta = T/T_{\mathrm{m}}\,.$$

The determined integral is computed with the use of splines (spline quadrature) [3] in the module of spline approximation; the same procedures as for the computation of splines are used.

The objective function on each iteration of minimization is found by an individual function-type procedure to which the running values of the Stark and Biot similarity numbers are transmitted; for these values the temperature on the billet surface is determined at the times from the initial time to the final one with an assigned step and then the next value of the objective function is found from the deviation of the computed temperatures from the temperature at the corresponding points of the experimental curve.

To test the program we took the curve of heating of the cylinder (Sk = 0.75 and Bi = 0.075) as the experimental curve, [4, p. 123]. Different versions of the initial data were checked. The limits of variation of Sk and Bi were assigned in the range from 0 to 2. In this range, we selected the values of the initial approximation of Sk and Bi. The values of the errors ε and ε_1 varied from 10^{-6} to 10^{-2}. The calculations were performed on a Pentium-133 personal computer. Depending on the version of combination of the initial data the calculation time was from 2 to 40 min with the number of iterations from 60 to 2400.

The point of minimum was attained irrespective of the selected point of initial approximation. In the context of minimization of calculation time for the acceptable accuracy of obtaining the result (to 1% for Sk and to 2% for Bi) we recommend $\varepsilon = \varepsilon_1 = 10^{-4}$. The calculation time depends on selection of the values of the point of initial approximation.

Thus, the developed software makes it possible to determine, from the available experimental curve of the process of heating, the Stark and Biot similarity numbers for a specific industrial furnace and hence the coefficients of heat exchange by convection and radiation for this furnace.

NOTATION

δ, objective function; $\mathrm{Fo_h}$, relative time (Fourier similarity number) of the process of heating (identification time); k, number of experimental points; Θ_i and $\Theta_{\mathrm{e}i}$, relative temperatures on the billet surface obtained by calculation and by experiment; Fo, Fourier similarity number; a, thermal diffusivity of the metal, $\mathrm{m^2/h}$; t, running time, h; R, cylinder radius, m; Θ, relative temperature; T, temperature on the billet surface, K; T_{m}, temperature of the heating medium, K.

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