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SELECTION OF THE TEMPERATURE REGIME OF METAL HEATING BY AN OXIDATION MINIMUM BASED ON THE METHOD OF MAIN OPTIMIZATION

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The authors carry out a comparative analysis of the methods of variational calculus and main asymptotic optimization as applied to the solution of the problem of optimum control of metal heating by using the scaling-minimization criterion.

In earlier works [1, 2], a solution is given for the problem of selecting an optimum regime of heating metal by the minimum of fuel consumption using the method of main asymptotic optimization. To develop methods of optimum control and with the aim of selecting a standard method, in the present work we solved the optimization problem using the criterion of scaling minimization. It should be noted that, for these problems, various mathematical approaches are widely used: the method of investigation of functions of classical analysis, the method of variational calculus, dynamic programming, Pontryagin's principle of maximum, the methods of linear and nonlinear programming, and the method of penalty functions ([3-7], etc.). The selection of the method is conditioned by the mathematical description of the object of optimization: the mathematical model, the goal function, imposed limitations, etc. In particular, in [3] a solution is given for the problem of optimum control of heating thermally large bodies of various geometries by the minimum of scaling based on the method of classical variational calculus.

It should be noted that the optimum solution obtained [3] has some drawbacks: first, it is approximate and, consequently, does not give an exact result; second, it is obtained from the Euler equation, which, generally speaking, is a necessary condition for the extremum of the functional; third, the Euler equation has no unique solution (therefore, it is not clear what extremum should be selected); fourth, as is noted in [3], it is difficult to control heating by the surface temperature. It is suggested in [3] that the last drawback be overcome by determining, from equality of the heat fluxes (from the conditions of external and internal heat exchange), the time dependence of the temperature of the heating gases.

We suggest solving the problem of heating with minimum scaling based on the method of main optimization. Use of this method opens up the possibility of dividing the problem of optimum control into simpler subproblems. In a system with an excess time for functioning, the optimum trajectory strives to be in the region of phase space where this is advantageous from the viewpoint of the optimality condition. The trajectory will consist of three portions: attainment of the main regime; the main regime; receding from it. Here, the central (main) portion of the trajectory is determined by the asymptotic properties of optimum trajectories, while the extreme portions are determined by the boundary conditions.

The mathematical formulation of the problem of heating metal using the minimum of scaling has the form [3]

$$\frac{dT_{\text{m}}}{d\text{Fo}} = \frac{k}{k_3 - 1} (T_{\text{sur}} - T_{\text{m}}) \, ; \tag{1}$$

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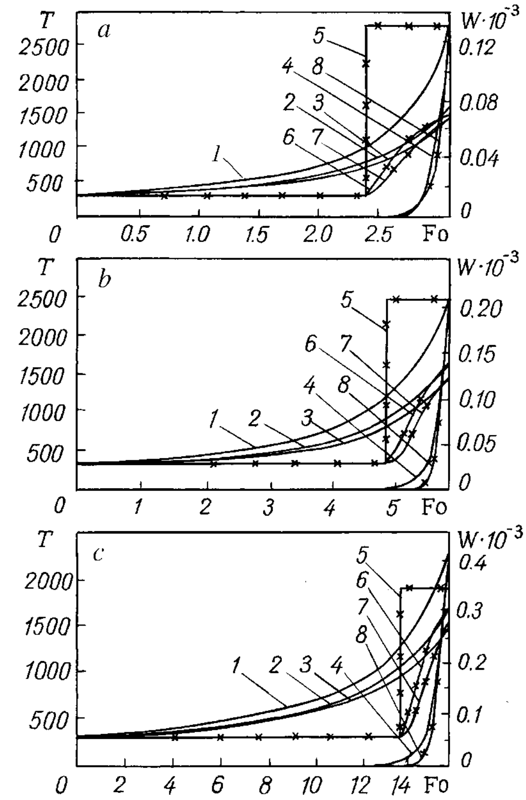

Fig. 1. Dynamics of the change in the temperature of the heating gases (1, 5) and the surface (2, 6) and center (3, 7) of the metal and in the magnitude of the relative burning loss (4, 8) in heating classically shaped bodies calculated by the method of variational calculus (solid curves) and main optimization (asterisked curves), respectively: a) sphere; b) cylinder; c) plate. T, K.

$$T_{\mathrm{m}}(0) = T_0\,; \quad T_{\mathrm{m}}(\mathrm{Fo_f}) = T_{\mathrm{m.f}}\,; \tag{2}$$

$$W^{1/h}(\mathrm{Fo_f}) = \int_0^{\mathrm{Fo_f}} \exp\left(\frac{-\beta}{T_{\mathrm{sur}}(\mathrm{Fo})}\right) d\mathrm{Fo} \to \min_{T_{\mathrm{sur}}}\,. \tag{3}$$

To take into account the above-described drawbacks of the method of variational calculus, we supplemented the mathematical model with an equation that connects the surface temperature with the temperature of the smoke (heating gases):

$$\frac{dT_{\mathrm{sur}}}{d\mathrm{Fo}} = \mu\,(T_{\mathrm{s}} - T_{\mathrm{sur}}) \tag{4}$$

subject to a boundary condition of the form

$$T_{\mathrm{sur}}(\mathrm{Fo_f}) = T_{\mathrm{sur.f}}\,. \tag{5}$$

This gives the possibility of influencing the surface temperature by changing the temperature of the furnace.

As a result, the problem of optimum control of metal heating from the initial temperature to a prescribed one can be formulated as follows. It is required that the temperature of the stack gases T_{s} be selected from a certain range $T_{\mathrm{s1}} \le T_{\mathrm{s}} \le T_{\mathrm{s2}}$, which is determined by the technological operating mode of the furnace, in

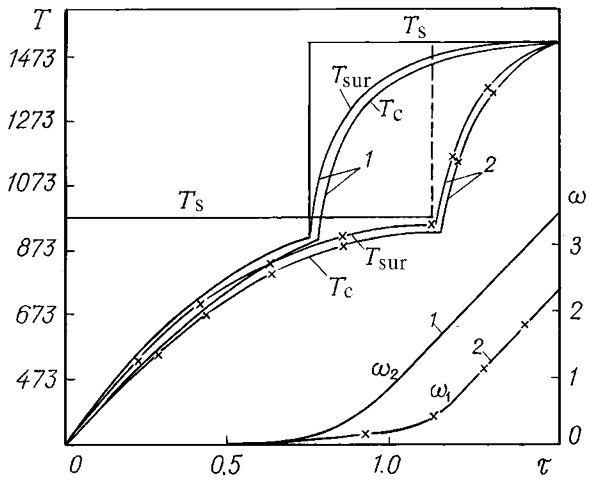

Fig. 2. Dynamics of the change in the temperature fields and the scaling in heating an ingot of dimensions 0.125×0.125 m according to the base (1) and optimum (2) regimes. τ, h; ω, kg/m^2.

such a manner that the minimum value of functional (3) is provided for solutions of system (1) and (4) that satisfy conditions (2) and (5).

Using the method of main asymptotic optimization, it was proved earlier [8] that the optimum change in the furnace temperature is provided by two-stage heating:

$$T_s\,(\text{Fo}) = \begin{cases} T_{s1} & \text{for } 0 \le \text{Fo} \le \text{Fo}^*\,, \\ T_{s2} & \text{for } \text{Fo}^* < \text{Fo} \le \text{Fo}_f\,. \end{cases}$$

The instant of switching Fo^* is selected so as to provide metal heating to the required temperature with a prescribed accuracy:

$$|\,T\,(\text{Fo}_f) - T_{\text{m.f}}\,| \le \varepsilon\,.$$

We developed software to compare two optimum trajectories obtained on the basis of variational calculus [3] and the method of main optimization.

For a numerical experiment, the following initial data were taken: $T_0 = 273$ K; $T_{\text{m.f}} = 1498$ K; $h = 0.7$; $\beta = 16570$ K; Bi = 0.78; the Fourier number is Fo = 3.10 for a sphere, 5.79 for a cylinder, and 15.44 for a plate.

In heating according to the optimum regime by the obtained method of variational calculus the relative burning loss of metal is: $W = 0.125{\cdot}10^{-3}$ for a sphere, $0.192{\cdot}10^{-3}$ for a cylinder, and $0.389{\cdot}10^{-3}$ for a plate. In the case of calculations by the method of main optimization, we have $0.119{\cdot}10^{-3}$ for a sphere, $0.181{\cdot}10^{-3}$ for a cylinder, and $0.382{\cdot}10^{-3}$ for a plate.

Graphs of the change in the temperature of the heating gases, the surface, and the metal and in the magnitude of the relative burning loss of the metal in heating bodies of various geometries obtained by different methods of optimization are given in Fig. 1.

An analysis of the results showed that the best effect is attained by the method of main optimization. It is obvious that in all cases a regime of change in the surface and furnace temperatures is obtained that provides lower oxidation than was suggested in [3]: the relative burning loss of metal turned out to be 4.8% less in heating a sphere, 5.7% less in heating a cylinder, and 1.8% less in heating a plate.

Thus, the analysis of the results proved the efficiency of the proposed method of main optimization in comparison with the method of variational calculus. It should be noted that earlier in [8] the advantage of the developed method in comparison with solution of the problem of optimization by the principle of maximum was shown.

Subsequently, the procedure for determining the optimum temperature regime was used to refine the regimes of heating high-carbon steels (70 K) in the heating furnace of the 320/150 mill of the Belarusian Metallurgical Works. The calculation results are given in Fig. 2. It is obvious that the amount of scaling deceased from 3.4 (the base regime) to 2.4 kg/m^2 (the optimum regime). To realize a theoretical two-stage graph of heating under practical conditions, the regime was transformed to a four-stage one. The optimum regimes developed underwent laboratory and industrial testing and were incorporated at the Belarusian Metallurgical Works.

NOTATION

T, temperature; T_m, temperature of the metal; T_{sur}, surface temperature; $T_{sur.f}$, final temperature of the surface; T_c, temperature of the center; T_0, initial temperature of the metal; $T_{m.f}$, final temperature of the metal; T_s, temperature of the smoke; T_{s1} and T_{s2}, minimum and maximum possible temperatures of the gases in the furnace; τ, time; $k = k_1k_2k_3$, coefficient of inertia of the body ($k = 6$ for a plate, $k = 8$ for a cylinder, and $k = 10$ for a sphere); k_1, coefficient of mass loading ($k_1 = 1$ for a plate, $k_1 = 2$ for a cylinder, and $k_1 = 3$ for a sphere); k_2, coefficient of averaging of the heat-flux density over the body cross section ($k_2 = 2$ for all the bodies considered); $k_3 = (k_1 + 2)/k_1$, coefficient of the mass mean temperature ($k_3 = 3$ for a plate, $k_3 = 2$ for a cylinder, and $k_3 = 1.67$ for a sphere); W, relative burning loss of metal; Bi $= \alpha S/\lambda$, Biot number; α, coefficient of convective heat exchange; λ, thermal conductivity; Fo $= \alpha\tau/S^2$, Fourier number; a, thermal diffusivity; S, calculated size of the body; Fo$_f$, final value of the Fourier number; ω, amount of scale; ε, prescribed accuracy of the calculation; μ, coefficient characterizing the dynamics of the heating; h and β, constants characterizing the dynamics of the scaling. Subscripts: m, metal; sur, surface; c, center; f, final value; s, smoke (heating gases).

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