Journal of Engineering Physics and Thermophysics, Vol. 79, No. 4, 2006

STUDY OF A CARBON-CERAMIC COMPOSITE MATERIAL UNDER HIGH-TEMPERATURE THERMAL ACTION

L. I. Guseva,[a] **Yu. D. Khodzhaev,**[b] **and V. M. Yudin**[b]

536.24

The results of testing a carbon-ceramic composite material exposed to multiple high-temperature thermal action are given. The thermophysical characteristics of the material under study are restored based on these results and with the methods of solution of inverse heat-conduction problems.

A carbon-ceramic composite material developed at the Institute of Aviation Materials (Moscow) may be considered for the large-scale model of a hypersonic aircraft as the thermal protection of its most thermally stressed elements. Investigations of the efficiency of this material in different operating regimes followed by determination of its thermophysical characteristics extend the range of its application.

Samples of the carbon-ceramic composite material with dimensions 20 × 30 × 9 mm and a volume density $\rho = 2.13$ g/cm^3 were tested on a radiative-heating bench for a heating rate of $\partial T/\partial\tau = 5$ K/sec in four regimes:

(1) $T_w = 450$ K and $\tau_e = 36$ sec;
(2) $T_w = 600$ K and $\tau_e = 64$ sec;
(3) $T_w = 900$ K and $\tau_e = 108$ sec;
(4) $T_w = 1500$ K and $\tau_e = 210$ sec.

We carried out eight experiments: we reproduced regime 1 in test Nos. 1 and 2, regime 2 in test Nos. 3 and 4, regime 3 in test No. 6, and regime 4 in test Nos. 7 and 8.

An analysis of the testing results has shown that multiple thermal action did not affect the state of working surfaces of the composite. In all the nonstationary regimes of heating, we measured the temperature profiles across the thickness of the material under study using thermocouples of diameter 0.2 mm whose thermoelectrodes are butt-welded. Since the carbon-ceramic composite material is conducting, we utilized a special antishunting composition, which ensured high-quality measurement conditions, using new technologies to eliminate shunting between the thermocouple electrodes.

The thermophysical characteristics of the thermal protective carbon-ceramic composite material were determined by the method of solution of an inverse coefficient problem for coked materials [1] under the assumption that the material under study is undecomposable and the thermal conductivity and the heat capacity are dependent just on temperature and have finite-dimensional representations in the form of splines $\lambda(T) = \{\lambda_1, \lambda_2, ..., \lambda_k\}$ and $c(T) = \{c_1, c_2, ..., c_k\}$. The values of $\lambda(T)$ and $c(T)$ were restored from the condition of finding the minimum of the quadratic residual of experimental and calculated temperatures:

$$S\{\lambda_1, ..., \lambda_k; c_1, ..., c_k\} = \frac{1}{N}\sum_{n-1}^{N} \frac{1}{\int_0^{\tau_e} \mu_n d\tau} \int_0^{\tau_e} \mu_n \left[T^c(x_n, \tau) - T_n^e(\tau)\right]^2 d\tau = \min , \quad n = 1, 2, ..., N . \tag{1}$$

The calculated values of the temperature $T^c(x_n, \tau)$ were computed by solution of the one-dimensional equation of nonstationary heat conduction

---

[a]M. M. Gromov Flight-Research Institute, Zhukovskii, Russia; [b]N. E. Zhukovskii Central Aerohydrodynamics Institute, 1 Zhukovskii Str., Zhukovskii, 140160, Moscow Region, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 79, No. 4, pp. 194–196 , July–August, 2006. Original article submitted May 6, 2006.

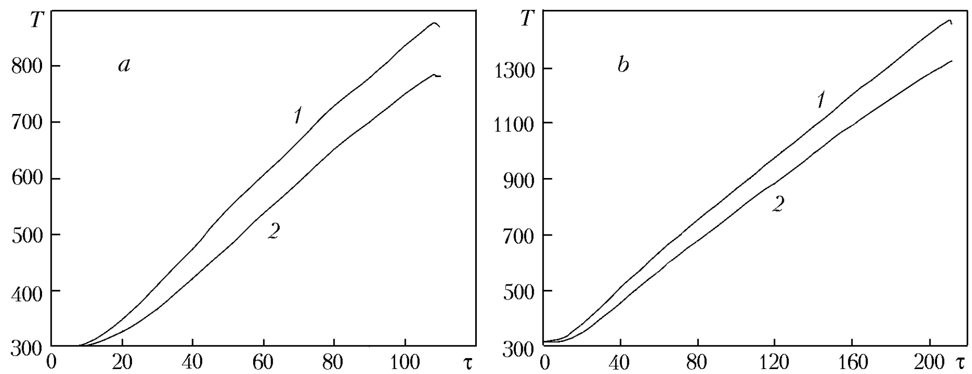

Fig. 1. Change in the temperature on the heated (1) and reverse surfaces of a sample of carbon-ceramic composite material for two regimes of heating: a) regime 3; b) regime 4. T, K; τ, sec.

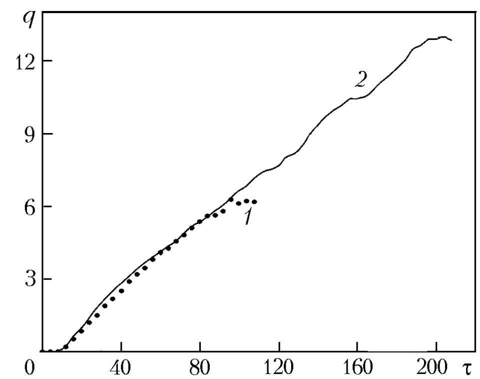

Fig. 2. Calculated values of the heat flux on the reverse surface of a carbon-ceramic composite material for two regimes of heating: 1) regime 3; 2) regime 4. q, kW/m^2; τ, sec.

$$\rho c\,(T)\,\frac{\partial T\,(x,\tau)}{\partial \tau}=\frac{\partial}{\partial x}\left[\lambda\,(T)\,\frac{\partial T\,(x,\tau)}{\partial x}\right],\quad 0<x<\delta\,,\quad 0\le\tau\le\tau_{\mathrm{e}}\,, \tag{2}$$

boundary conditions for which were specified in the form of a set of the initial temperature distribution

$$T\,(x,0)=T_0\,(x)\,,\quad 0\le x\le\delta \tag{3}$$

and the boundary conditions on the exterior (x = 0) and interior (x = δ) surfaces respectively:

$$T\,(0,\tau)=T_0\,(\tau)\,,\quad -\lambda\,(T\,(\delta,\tau))\,\frac{\partial T\,(\delta,\tau)}{\partial x}=q\,(\tau)\,,\quad 0<\tau\le\tau_{\mathrm{e}}\,. \tag{4}$$

Experimental information obtained in the process of nonstationary heating of the material under study was represented in the form

$$T^{\mathrm{e}}\,(x_n,\tau)=T_n^{\mathrm{e}}\,(\tau)\,,\quad 0<x_n<\delta\,,\quad 0\le\tau\le\tau_{\mathrm{e}}\,,\quad n=\overline{1,N}\,.$$

In connection with the ravine character of the residual functional $S\{\lambda(T),c(T)\}$, the dependences $\lambda(T)$ and $c(T)$ were determined by the method of successive minimization combined with the method of conjugate gradients. First we carried out minimization of the functional (1) by the conjugate-gradient method under the assumption that $\lambda(T)$ and $c(T)$ are linear throughout the temperature range under study; thereafter we increased the number of intervals until the

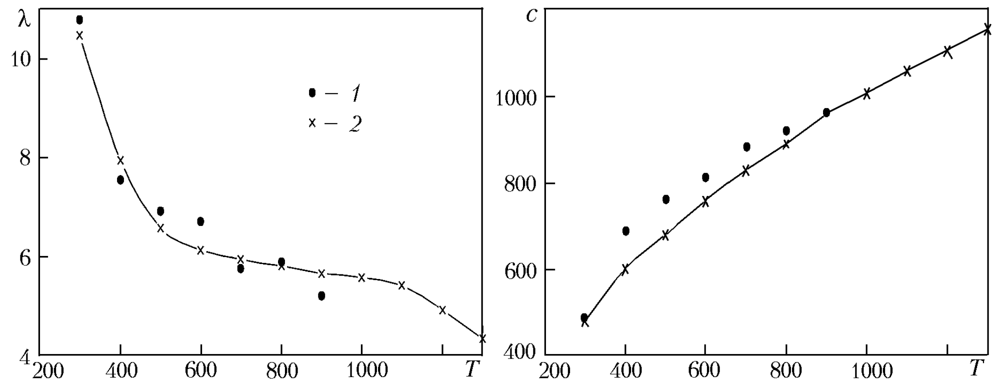

Fig. 3. Thermophysical characteristics of a carbon-ceramic composite material in different temperature ranges: 1) 300–900; 2) 300–1300 K. λ, W/(m·K); c, J/(kg·K); T, K.

standard deviation of the calculated values of temperature from the experimental ones became smaller than the measurement error or ceased to decrease. At each step, the minimum of $S\{\lambda_1, .., \lambda_k; c_1, .., c_k\}$ was sought by the conjugate-gradient method.

Figures 1 and 2 give experimental curves of change in the temperature and the heat fluxes; these curves have been calculated with the method of an additional wall. As the additional wall, we used a plate manufactured from a highly efficient TZMK-10 heat-insulation material with known properties. The change in temperature was fixed on one side of it, whereas a zero heat flux was fixed on the other. The thermophysical characteristics of the carbon-ceramic composite material in the temperature ranges 300–900 K and 300–1300 K, which have been restored from the initial data, are shown in Fig. 3.

The standard deviation of the calculated temperature values from the experimental ones was S_{st} = 1.43 K and the maximum deviation was S_m = –3 K for the values of $\lambda(T)$ and $c(T)$ obtained at ΔT = 300–900 K; in the temperature range 300–1300 K, we had S_{st} = 2.31 K and S_m = –5.41 K.

NOTATION

k, number of parameters in the representation of the $\lambda(T)$ and $c(T)$ sought; n, No. of the temperature-sensitive element; N, number of temperature-sensitive elements; $q(\tau)$, heat flux; S_m and S_{st}, maximum and standard deviations of the calculated values of temperature from the experimental ones; $S\{\lambda_1, .., \lambda_k; c_1, .., c_k\}$, functional; T, temperature; $T_0(x)$, initial temperature distribution; $T_n^e(\tau)$, experimental temperature values; x, coordinate; x_n, location of temperature-sensitive elements; δ, material thickness; μ_n, weight factors characterizing the reliability of the experimental temperatures; τ, experimental time. Subscripts and superscripts: e, experimental; c, calculated; m, maximum; st, standard.

REFERENCES

1. V. M. Yudin, Inverse problem of definition of the thermal characteristics of coked composite materials, in: *Proc. 4th Int. Conf. "Inverse Problems: Identification, Design and Control,"* 2–6 July 2003, Moscow, Russia.