Journal of Engineering Physics and Thermophysics, Vol. 68, No. 2, 1995

HEATPROOF CHARACTERISTICS OF COMPOSITE MATERIALS IN THE CASES OF CONSTANT AND VARIABLE FLOW PARAMETERS

V. L. Sergeev

UDC 533.951.7:536.24.01

Results of an experimental investigation of failure characteristics of certain types of composite materials under the quasisteady and unsteady action of a high-enthalpy air flow at atmospheric pressure are presented.

Composite materials are finding increasingly widespread use in engineering [1-5]. Among these materials are glass-reinforced plastics ($\rho \cong 1.6$ g/cm^3), organoplastics ($\rho \cong 1.2-1.3$ g/cm^3), and carbon fiber-reinforced plastics ($\rho \cong 1.4$ g/cm^3), for which silica, polyamide, carbon, and other fibers are reinforcements. Epoxy, polyurethane, and phenolic resins serve as a binder. Composite materials offer, in some cases, greater strength and less weight than aluminum [6]. Broad prospects for using the enumerated materials are opened up in modern industrial installations involving high-intensity heat transfer.

To compare the efficiency of materials, use is made of their heatproof characteristics such as linear removal, weight removal, dimensionless removal, the effective enthalpy of the materials, and the surface temperature [7].

The effective enthalpy of a material is determined by the formula

$$I_{\text{ef}} = \left(q_0 \frac{I_0 - I_w}{I_0 - I_{w0}} - \varepsilon\sigma T_w^4 \right) / G_{\text{weight}}, \tag{1}$$

where q_0 is the heat flux in the region of the stagnation point measured by a heat flux transducer; I_{w0} is the enthalpy of the gas on the transducer surface; I_0 and I_w are the enthalpy of the gas in the stagnated flux and on the material specimen surface; G_{weight} is the weight removal of material per unit time per unit area; $\varepsilon\sigma T_w^4 = q_r$ is the correction for radiation from the specimen surface; $q/(I_0 - I_{w0}) = \alpha/c_p$; $G_{\text{weight}}/(\alpha/c_p) = \overline{G}$ is the dimensionless rate of removal.

An experimental method of estimating the characteristics of heatproof materials under near-natural conditions is, in particular, the study of their behavior in an air plasma jet at the outlet of an electric arc heater. In the present work we used a linear-circuit plasmatron with squeezing of the discharge with an air vortex [8]. The plasmatron produces a heated air jet 10–30 mm in diameter with enthalpy in the range of 10,000–60,000 J/kg that is suitable for testing cylindrical specimens of materials 14 mm in diameter. The design of the heater, the volt-ampere and thermal characteristics, and the jet parameters were considered in [8].

In experiments on the failure of material specimens in the case of constant flow parameters specimens placed in a cooled copper sleeve in the shape of a frustrum of a cone, beyond which they extended 1–2 mm, were moved with a motor as they were burned using a special mechanism so that the distance from the nozzle to the specimen remained constant. The displacement of the specimen (linear burning) was recorded by a loop oscillograph using a displacement transducer that incorporated two variable resistances. The movable contact of one resistance was attached to the movable portion of the specimen feeder, and the second resistance was used to set zero current through the oscillograph vibrator for the initial position of the specimen and to limit the current through it.

In special experiments we determined the heat flux to the specimen by an exponential method [8] using a copper transducer and the stagnation pressure usingh a cooled copper transducer. To determine the enthalpy of

Academic Scientific Complex "A. V. Luikov Institute of Heat and Mass Transfer of the Academy of Sciences of Belarus," Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 68, No. 2, pp. 217-224, March-April, 1995. Original article submitted October 8, 1993.

 1062-0125/95/6802-0186$12.50

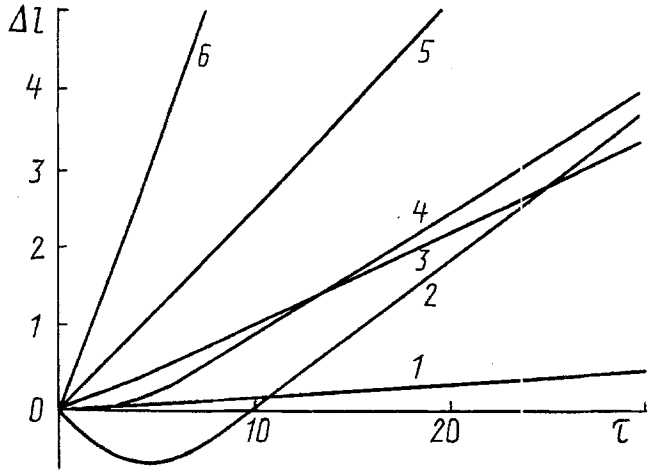

Fig. 1. Change in specimen length with time: 1) graphite; 2) organoplastic (polyamide fiber, epoxy binder); 3) carbon fiber-reinforced plastic (graphite thread, phenol-rubber-phosphorus binder); 4) organoplastic (Arimid polyamide fiber, polyurethane binder); 5) glass-reinforced plastic (silica fiber, epoxy binder); 6) fluoroplastic; I_0 = 26,000 kJ/kg; q = 1.2 kW/cm^2; α/c_p = 0.4 kg/(m^2·sec). Δl, mm; τ, sec.

the flow acting on the specimen, we applied [9] contact and noncontact methods: 1) from the heat flux and the stagnation pressure by using the dependence of Fay and Riddell, which relates these parameters and is reduced [8] to the form

$$q = 4.5 \cdot 10^{-4} R^{-0.5} p_0^{0.25} (p_0 - p_\infty)^{0.25} (I_0 - I_w), \quad (2)$$

where q is the specific heat flux, kW/m^2; R is the transducer spout radius, m; p_0 is the stagnation pressure, N/m^2; I_0 is the stagnation enthalpy, kJ/kg; 2) using the Gray transducer; 3) the method of relative intensity of spectral lines; 4) from the line broadening H_β. The first method was the fundamental one. Comparison of the results of measurements by different methods showed [8, 9] that they are in satisfactory agreement.

The heat flux to a flat end of a cylinder of radius R (the specimen usually used) is related to the heat flux to a sphere of radius R in the region of the stagnation point (2) by the relation [8] $q_{fl}/q_{sph} = 0.65$.

The brightness temperature of the end of a specimen was measured by a standard pyrometer. We determined the actual surface temperature T_w from literature data on the emissivity factor of the materials in question and ones close to them in their properties.

By using a computer program we calculated the parameters of the flow q, I_0, and α/c_p and specimen material removal: dimensional and dimensionless rates of failure determined from linear removal and weight removal with and without account taken (when necessary) of a coke layer and the corresponding values of the effective enthalpy of the materials. The linear removal rates were determined from the curves of change in the specimen length in time on linear portions that corresponded to quasisteady regimes of failure (Fig. 1).

Whereas for fluoroplastic and glass-reinforced plastic the rate of removal was established virtually, from the onset of the process of failure, for organoplastics and carbon fiber-reinforced plastics there was a more or less extended period for establishment of the removal rate. In some organoplastics we observed swelling of the specimens in the initial period (Fig. 1, curve 2), which is shown in the figure as a negative change in the specimen length. Swelling of heatproof coatings is noted in the literature [10] as a factor that contributes to enhancing the efficiency of the material. From Fig. 1 we can infer (curves 2 and 4) that the role of organoplastic swelling is ambiguous and depends on the established rate of removal, the time of exposure to the high-enthalpy flow, and the value of the parameter a/c_p or the stagnation pressure. For the majority of the composite materials there was a rather thick layer (up to several mm) of highly porous material of low strength on the specimen surface after the experiment. It is evident that with an increase in the stagnation pressure this layer will fail. Inclusion of the disintegration zone

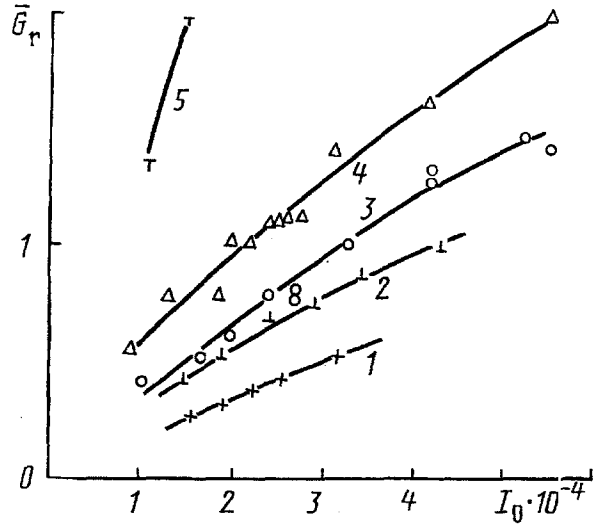

Fig. 2. Dimensionless rate of failure vs stagnation enthalpy: 1) carbon fiber-reinforced plastic; 2) organoplastic; 3) glass-reinforced organoplastic; 4) glass-reinforced plastic; 5) fluoroplastic. I_0, kJ/kg.

in the removed material leads, for example, to a 25% increase in the dimensionless rate of removal for organoplastic 4. The material swelling and associated misalignments of the specimens led to certain errors in measuring the linear rate of burning. On the other hand, there was an inevitable overestimation of the removal rate in its determination from the change in the specimen weight before and after the experiment; it is associated with material removal from the lateral surface of the specimen. Use of the cooled protective sleeve in which the specimen moved permitted minimization of this error. The ratio $\bar{G}_{\text{weight}}/\bar{G}_l$ was 1–1.1 for the glass-reinforced plastic and carbon fiber-reinforced plastic and 1–1.2 for the organoplastics. The results obtained (Figs. 1 and 2) indicate that such materials as organoplastics and carbon fiber-reinforced plastics provide substantially lower rates of removal than glass-reinforced plastics in a wide enthalpy interval for air flow at atmospheric pressure, which makes them appealing for use in aerospace engineering. The enthalpy range of the air was 900–56,000 kJ/kg. The dimensionless removal of organoplastics is two or more times less than for glass-reinforced plastic. The result obtained is explained by the formation of a comparatively thick porous coke layer for organoplastics in heating that offers high heatproof properties. The heating time before the quasisteady regime of failure is established is also substantially longer for an organoplastic coating.

According to (1), the effective enthalpy of a material is sensitive to the surface temperature. Whereas for glass-reinforced plastic the surface temperature was 2700 to 3100 K for values of the enthalpy of the flow from 10,000 to 60,000 kJ/kg, for organoplastic it was 3200 to 3600 K, and for carbon fiber-reinforced plastic 3200 to 3800 K. As a result, the effective enthalpy (heat of ablation) of glass-reinforced plastic for an enthalpy of the flow up to 20,000–30,000 kJ/kg is higher than for organoplastic and carbon fiber-reinforced plastic and amounts to 12,000 to 18,000 kJ/kg. For larger values of the enthalpy of the flow the effective enthalpies of organoplastic and carbon fiber-reinforced plastic begin to exceed this value for glass-reinforced plastic.

It is well known that the effective enthalpy of composite materials is determined by an expression of the form

$$I_{\text{ef}} = \Delta Q + c\,(T_w - T_0) + \gamma \frac{q_0}{\alpha / c_p}, \tag{3}$$

where ΔQ is the heats of phase transformations, chemical reactions, etc., depending on the type of material; $c(T_w - T_0)$ is the heating of the material to the failure temperature; $\gamma q_0/(\alpha/c_p)$ is the amount of heat blocked due to blowing into the boundary layer. The last term in expression (3) can be represented as a function of the stagnation enthalpy as follows: $I_{\text{blow}} = \gamma(I_0 - I_w)$, where $\gamma = f(I_0, I_w, \alpha/c_p)$. In this connection in the general case the dependence of the effective enthalpy of materials on the stagnation enthalpy of the gas flow is nonlinear, which

is confirmed by experiment. In certain (rather narrow) ranges of change in the enthalpy of the gas and other parameters the dependences in question can be approximated by straight lines. An example of this dependence for glass-reinforced plastic is given in [7].

In many cases the dimensionless rate of removal as a function of the enthalpy of the flow at near-atmospheric pressure (Fig. 2) can be approximated by dependences of the form

$$\overline{G} = \overline{G}_\infty \left[1 - \exp - \frac{I_0 - I_w}{I_*} \right], \tag{4}$$

where $\overline{G}_\infty$ and I_* are constants.

By using (4) we can determine the effective enthalpy by means of expression (1) or

$$I_{ef} = \left(1 - \frac{q_r}{q} \right) (I_0 - I_w)/\overline{G}. \tag{5}$$

Experimental data for different types of composite materials (ρ = 1.32–1.76 g/cm^3) are described satisfactorily by the formula

$$\frac{H_{ef} - C}{I_0} = AI_0 + B, \tag{6}$$

where A, B, and C are constants for a given type of material; $H_{ef} = I_{ef} - I_{ef_0}$; I_{ef} is the experimental data; I_{ef_0} is the value of the effective enthalpy of the material at $I_0 \approx I_w$, $I_{ef_0} \approx \Delta Q + c(T_w - T_0)$.

Above, we considered characteristics of the materials obtained for constant flow parameters. Typical operating conditions for materials used for a heat shield for aircraft are time-variable enthalpy and pressure of stagnation of the gas flow in the region of the stagnation point and heat flux to the surface. The rate of change of the heat flux can attain hundreds of W/(cm^2·sec) [11].

As theoretical estimates show [12-14], the characteristics of failure of composite materials under unsteady conditions can be different from the corresponding characteristics for quasisteady conditions. In particular, in [14] it is shown that in the case of a linear change in the heat flux with time an unsteady effect can appear that is expressed as the difference of the linear removal rate from the corresponding (according to the instantaneous value of the heat flux) quasisteady rate. The unsteady effect depends on the type of material and the rate of change in the heat flux with time [14].

It is rather difficult to obtain an exact theoretical solution to the problem of unsteady failure of composite material coatings. In this connection experimental investigation of removal of composite materials under unsteady conditions is of interest. In the present work we ensured a change in the parameters of the flow in front of the material specimen with time by bringing the source of the air plasma jet, i.e., the electric arc heater, closer to it (or moving it away). The heater was displaced by an automatic device according to a prescribed program. We started the experiment with a constant distance from the specimen to the nozzle that corresponds to the heat flux q_1 until a quasisteady failure regime was established; then there was an increase (or a decrease) in the heat flux according to a near-linear law to some value q_2, after which the experiment continued with the new value of the heat flux up to the quasistationary failure regime. The chosen rates of displacement for the discharge chamber and the portion of the plasma jet permitted rates of change in the heat flux to the specimen of 120 to 420 W/(cm^2·sec).

The displacement of the discharge chamber was recorded by a loop oscillograph using an electric transducer. As in the case of the quasisteady regime of failure, the specimen as it burned up was moved using the mechanism of specimen displacement so that its end is in the same cross section during the experiment. The specimen was placed in the copper cooled sleeve in the shape of a frustum of a cone and was extended 1–2 mm beyond it. The position of the specimen end was controlled by a magnified image of it on the screen of an EOP-66 pyrometer and by photographs produced using an RFK-5 photocamera. Specimen burn-up was determined using an electric transducer that permitted conversion of the linear displacement into an electric signal recorded by the loop oscillograph. The measurement results were compared with the total change in the specimen length over the

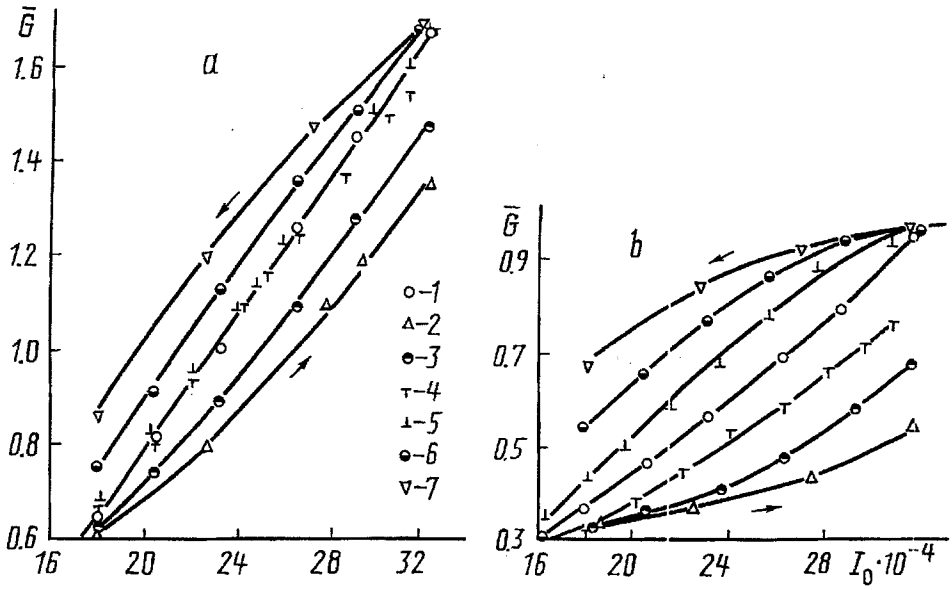

Fig. 3. Dimensionless removal vs enthalpy of the flux: 1) quasisteady conditions of failure; 2-7) unsteady conditions; 2-4) increase in the heat flux; 5-7) decrease in the heat flux; 2, 7) $dq/d\tau$ = 420 W/(cm^2·sec); 3, 6) 210; 4, 5) 120; a) glass-reinforced plastic; b) organoplastic.

time of the experiment. The brightness temperature of the specimen end surface was measured using the EOP-66 pyrometer.

In preliminary experiments we measured the heat fluxes and stagnation pressures in the cross section of the material specimen end as we brought closer or moved it away the discharge chamber. For this purpose we used a semiinfinite-body method for measuring the unsteady heat flux and a combined transducer that enabled us to measure a variable heat flux and pressure and enthalpy of stagnation [7]. The errors in determining the heat fluxes and the jet parameters were considered earlier [7] and amounted to 2% for the stagnation pressure, 10% for the heat flux, 12% for the enthalpy by the Gray method, and 14% for the enthalpy with the use of Eq. (2).

The curve of removal obtained on the oscillogram was approximated by the expression $s = A + B\tau + C\tau^2 + D\tau^3$, whose coefficients were found by the least-squares method. The linear rate of failure at a given instant was determined as the derivative $v = ds/d\tau$.

To calculate the coefficients A, B, C, and D, the burn-up rate, and the effective enthalpy of a material, we wrote a computer program.

We investigated the failure of materials with organic fibers, carbon fiber-reinforced plastic, glass-reinforced plastic, and fluoroplastic under the unsteady conditions described above. The tests performed showed (Fig. 3) that the unsteadiness of the parameters of the incoming flow can affect substantially the basic characteristics of material removal. The degree of deviation of the characteristics under unsteady conditions from the corresponding quasisteady characteristics depends on the kind of material and the rate of change of the heat flux.

For example, for the glass-reinforced plastic the dimensionless removal $\bar{G}$ is the same under unsteady and quasisteady conditions for a rate of change of the heat flux of 120 W/(cm^2·sec) and near-atmospheric pressure (Fig. 3a), and for $dq/d\tau$ = 420 W/(cm^2·sec) the unsteady removal $\bar{G}_{un}$ is less than the quasisteady one (up to 23%) in the case of an increase in the thermal load and greater than the quasisteady one (up to 30%) in the case of a decrease in it. Each experiment with a change in heat flux started after a quasisteady failure regime was attained for a constant heat flux, as a result of which the unsteady characteristics in Fig. 3 are close to the steady ones on the left-hand side of the plot for an increase in the load and on the right-hand side for a decrease in it.

For the materials with organic fibers, the deviation of the characteristics in the unsteady case from those in the quasisteady one is more substantial. In particular, for the material whose characteristics are given in Fig. 3b it attains 85%. A distinct discrepancy in the removal rate under unsteady and quasisteady conditions occurs even for a rate of change of the heat flux of 120 W/(cm^2·sec).

The removal of carbon fiber-reinforced plastic at the end of the unsteady portions of the program differed by 50% from the quasisteady one for the highest investigated rate of change of the heat flux.

For the fluoroplastic, the unsteady characteristics coincide with the quasisteady ones for all the investigated rates of change of the heat flux.

The observed unsteady effect that is expressed in a larger or smaller deviation of the removal characteristics from the quasisteady ones can be explained by the inertia of the processes of material heating and failure. The degree of inertia of these processes depends on type of material, i.e., on the predominance of some failure mechanisms or other. Therefore, we could expect that for the glass-reinforced plastic, for which melting of the filler is of importance in the failure mechanism and a relatively thin layer of disintegrated material forms, inertial properties of this layer will be less pronounced than for the thicker and more porous coke layer formed in the failure of the organic-fiber materials. As the heating rate increases, the deviation of the characteristics from the quasistationary ones should increase because of the inertia of the processes in the material, which is confirmed by experiment (Fig. 3).

The absence of unsteady effects for fluoroplastic found in the present work is confirmed by published data and is associated with the fact that the failure zone for this material is concentrated in a narrow surface layer and the mechanism of failure changes quite rapidly with changing ambient conditions.

The unsteady effects in the case of variable flow parameters also manifest themselves in such material characteristics as the disintegration zone thickness $\Delta l_{d.z}$ (the thickness of the surface layer with substantially changed properties) and the surface temperature. The deviation of $\Delta l_{d.z}$ from the quasisteady characteristic depends on the sign and magnitude of the derivative $dq/d\tau$ and on the type of material.

The obtained dependences of the surface temperature on the enthalpy of the flow in unsteady regimes are similar to the curves of dimensionless removal, but the deviations from the quasisteady characteristics are relatively small (up to 10–15%).

Account for the disintegration zone (i.e., its inclusion in the removed material) leads to a greater degree of closeness between the unsteady and quasisteady characteristics of removal, which suggests that with an increase in αc_p (with an increase in the stagnation pressure) the unsteady effects will decrease.

The results of measuring the relative dimensionless rate of removal under unsteady conditions $\overline{G}_{un}/\overline{G}_{st}$ as a function of the heat flux and the rate of its change with time for all the materials in question can be generalized by the following expression:

$$\frac{\overline{G}_{un}}{\overline{G}_{st}} = \frac{A\left(\frac{dq}{d\tau} - 420\right)\left(\frac{dq}{d\tau} - 210\right)}{27000} + \frac{B\left(\frac{dq}{d\tau} - 420\right)\left(\frac{dq}{d\tau} - 120\right)}{18900} + \frac{C\left(\frac{dq}{d\tau} - 210\right)\left(\frac{dq}{d\tau} - 120\right)}{63000}, \tag{7}$$

where the dimensionality of $dq/d\tau$ is W/(cm^2·sec), and

$$A = A_1 (q/q_{min})^a, \quad B = B_1 (q/q_{min})^b, \quad C = C_1 (q/q_{min})^c. \tag{8}$$

The values of the coefficients A_1, B_1, C_1 and the exponents a, b, c are constant for a given type of material and sign of $dq/d\tau$, and $q_{min} = 1.2$ kW/cm^2.

Thus, it is shown that depending on the rate of change of the heat flux and the type of material the dimensionless rate of removal and other characteristics differ from the quasisteady characteristics to a greater or lesser degree. To optimize a heat shield, we need to take account of the difference in the dimensionless removal rate under unsteady and quasisteady conditions, which can reach a factor of two or more.

We have obtained generalized dependences for the investigated materials for calculating the dimensionless rate under unsteady conditions. We have established the values of the parameters that separate the regions of unsteady and quasisteady failure.

REFERENCES

1. V. S. Avduevskii, B. M. Galitseiskii, G. A. Glebov, et al., Principles of Heat Transfer in Aeronautical and Rocket Engineering [in Russian], Moscow (1975).
2. S. J. Grisaf, Aérokosm. Tekhn., No. 9, 134-136 (1987).
3. G. I. Nazarov and V. V. Sushkin, Heatproof Plastics: A Handbook [in Russian], Moscow (1980).
4. V. N. Kirillov, I. V. Sobolev, and V. A. Efimov, Heat and Mass Transfer [in Russian], Vol. 7, Minsk (1972), pp. 382-386.
5. V. V. Vasiliev, V. D. Protasov, V. V. Bolotin, et al., Composite Materials: A Handbook [in Russian], Moscow (1990).
6. R. Demais, Aérokosm. Tekhn., No. 6, 191-192 (1987).
7. V. L. Sergeev, Unsteady Heat Transfer in the Region of a Stagnation Point [in Russian], Minsk (1988).
8. V. L. Sergeev and V. E. Grushko, High-Enthalpy Plasmatron for Testing Heatproof Materials in an Air Medium at Atmospheric Pressure [in Russian], Minsk (1993) (Preprint, ANK ITMO AN Belarusi).
9. V. L. Sergeev and E. V. Garkavyi, Inzh.-Fiz. Zh., **55**, No. 3, 383-388 (1988).
10. V. L. Strakhov and N. G. Chubakov, Inzh.-Fiz. Zh., **55**, No. 4, 575-581 (1988).
11. D. L. Peterson, F. E. Goweh, and C. Richardson, AIAA Paper, No. 70-255, 1-6 (1971).
12. N. A. Anfimov and Yu. V. Polezhaev, Heat and Mass Transfer [in Russian], Vol. 2, Minsk (1968), pp. 11-16.
13. B. M. Pankratov, O. M. Alifanov, A. Ya. Ivanov, and A. D. Markin, Inzh.-Fiz. Zh., **24**, No. 1, 75-83 (1973).
14. V. L. Sergeev, Inzh.-Fiz. Zh., **46**, No. 3, 469-475 (1984).