FAILURE PARAMETERS OF HEAT-SHIELDING MATERIALS IN THE NONSTATIONARY HEATING REGIME

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A technique is presented for estimating the failure parameters of heat-shielding materials. The basic possibility of determining the coefficient of thermal diffusivity using the self-similar regime method in the presence of mass being carried away from the material surfaces is demonstrated. An analytic expression is proposed for calculating the times for establishing a quasistationary failure regime and heating depth.

In calculating failure parameters of heat-shielding materials using methods examined in [1, 2], it is necessary to know their thermophysical properties, which, as a rule, are determined experimentally with one-sided or uniform heating of a sample of the material. In [3], it is shown that the value of the coefficient of thermal diffusivity, obtained with one-sided or uniform heating, can be very different. Apparently, for heat-shielding materials, operating under conditions of one-sided heating, the coefficients of thermal diffusivity are best determined under similar conditions.

One-sided heating can be done by different methods, of which the convective and radiative forms are most widely used. As is well known, the conditions for operation of heat-shielding materials differ considerably for radiative and convective heating. However, in many cases, especially when models with large dimensions are heated, it is more economical to use radiative heating rather than convective heating. In this connection, it is interesting to examine the conditions under which it is possible to exchange one one-sided heating source by another.

1. The experiments were conducted on a setup with radiative plasma heating in heat fluxes ranging from 0.2 to 1.3 kW/cm^2 with convective heating in flows of air and nitrogen and with radiative heating. The heating time in all cases equaled 30 sec. The basic scheme for the setup and its parameters are presented in [4]. In studying samples made of asbestos textolite, it was established that the depth to which it was pyrolyzed (total depth to which material is removed and charred) in the flux from the nitrogen plasma and radiative heating was the same for surface temperatures ranging from 2000 to 3000°K (Fig. 1a, curves 2 and 3, group I), in spite of the different amounts of material removed from the surface of the specimen. The same pyrolysis depths were also obtained for specimens in an air plasma, but this time for surface temperatures ranging from 2000 to 2500°K (Fig. 1a, curve 1, group I). It should be noted that the surface temperatures of the samples with equal heat flux densities were practically identical for all three types of heating.

In analyzing the experimental data obtained, it is easy to come to the conclusion that since the pyrolysis depths coincided for different values of the surface temperatures and heat fluxes, brought up to the material specimen, apparently, the change in the rate of displacement of the charring isotherms in all cases of heating examined up to the quasistationary regime was identical. Since, a quasistationary heating regime is established at the instant when the rate of displacement of the charring isotherms decreases to the value of a quasistationary rate of removal (Fig. 1b), the greater the quantity $\bar{V}_\infty$, the earlier the quasistationary heating regime is established and the pyrolysis depths will coincide in a shorter heating time interval.

Let us examine the change in the pyrolysis depth of asbestos Textolite as a function of time with convective heating in an air flow and radiant heating for heat fluxes of 0.16 and 1

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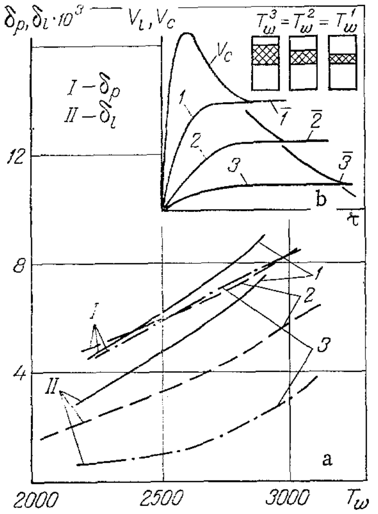

Fig. 1

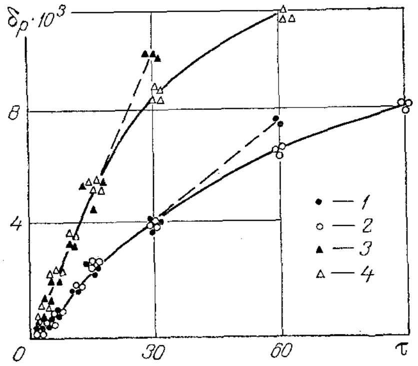

Fig. 2

Fig. 1. Dependence of the depth of pyrolysis and linear removal of asbestos textolite on the temperature of the surface (a) and scheme for changing the rates of displacement of the surface and the charring front for sample of heat-shielded material as a function of heating time (b): a) 1, 2, 3 are for air, nitrogen, and radiative heating; I — depth of pyrolysis; II — linear removal; b) 1, 2, 3 are the rates of displacement of the material surfaces in air and nitrogen flows and radiant heat fluxes in the nonstationary heating regime; $\bar{1}$, $\bar{2}$, and $\bar{3}$ are the same, but in a quasistationary heating regime for which $V_l = V_c = \bar{V}_\infty$. δ_p, δ_l, m; T, °K.

Fig. 2. Pyrolysis depth of asbestos Textolite with convective and radiative heating as a function of time(1, 3) convective heating in an air flow; 2, 4) radiative heating; 1, 2) heat flux 0.16 kW/cm^2; 3, 4) heat flux of 1 kW/cm^2. δ_p, m; τ, sec.

kW/cm^2. From Fig. 2, it is evident that with a heat flux of 0.16 kW/cm^2 pyrolysis depths are observed to coincide up to 30 sec of heating, while with a heat flux of 1 kW/cm^2 up to 15 sec of heating, i.e., up to the time that the pyrolysis depth does not change in a manner directly proportional to the heating time, which indicates the establishing of a quasistationary heating regime.

If the total thickness of the heated and removed material is kept in mind, then before the quasistationary heating regime is established in studying heat-shielding materials it is possible to replace the source of convective heating by radiative heating under the conditions that the heat flux entering into the material and the surface temperature of the material are maintained to be the same in both cases.

2. Analysis of the experimental results on the pyrolysis depth for asbestos, carbon, and fiberglass materials and quartz glass ceramics, obtained with radiative, convective, and combined radiative—convective forms of heating in a range of heat fluxes varying from 0.2 to 2.4 kW/cm^2, showed that specimens of heat-shielding materials are heated in the self-similar regime, i.e., $\delta_p \sim K\sqrt{a\tau}$. Some of the dependences obtained are shown in Fig. 3.

For all the materials investigated, the function $\delta_p = f(\sqrt{\tau})$ varies linearly right up to establishment of a quasistationary heating regime, so that it can be represented in the form

$$\delta_p = K\sqrt{a}\,(\sqrt{\tau} - \sqrt{\tau_\xi}). \qquad (1)$$

Here the coefficient $K\sqrt{a}$ equals the tangent of the angle of inclination of the straight line to the abscissa axis.

The deviation of the experimental values of δ_p from the dependences given by Eq. (1) for all materials investigated does not exceed 15%. To a certain degree, this is a result of the

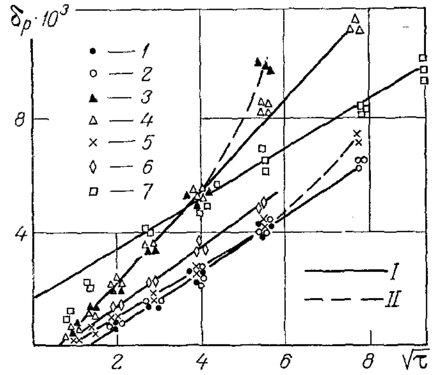

Fig. 3

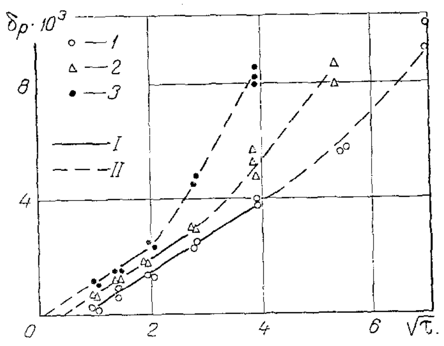

Fig. 4

Fig. 3. Pyrolysis depth of some heat-shielding materials as a function of heating time; I) self-similar heating regime; II) quasistationary heating regime; 1-4) asbestos Textolite; 5) fiberglass material with an epoxy binder; 6) quartz glass ceramic; 7) carbon layer; 1, 3) convective heating; 2, 4-7) radiative heating; 1, 2) heat flux of 0.16 kW/cm²; 3,4) heat flux of 1 kW/cm².

Fig. 4. Pyrolysis depth of nontransparent quartz glass ceramic with combined radiative—convective heating as a function of time: 1) q_c = 1.05 kW/cm²; 2) $q_c + q_r$ = (1.05 + 0.52) kW/cm²; 3) $q_c + q_r$ = (1.05 + 1.05) kW/cm²; I) self-similar heating regime; II) quasistationary regime.

fact that the error in the values of δ_p obtained, equal to the sum of δ_l and δ_T, is less than the error in determining δ_l and δ_T separately (18 and 20%).

If the coefficient K is somehow determined, then it is possible to determine the coefficient of thermal diffusivity as well. It follows from Eq. (1) that

$$K \approx \frac{1}{\sqrt{\mathrm{Fo}}}. \tag{2}$$

The solution of the problem of heating a semiinifinite insulated body with constant surface temperature [5] gives the expression

$$\frac{T^* - T_0}{T_w - T_0} = \mathrm{erfc}\left(\frac{\delta_p}{2\sqrt{a\tau}}\right). \tag{3}$$

For small values of Fo, the equation

$$\frac{T^* - T_0}{T_w - T_0} = \sqrt[3]{\mathrm{Fo}^2} \tag{4}$$

gives a quite good approximation to Eq. (3). However, as calculations have shown, the coefficients of thermal diffusivity agree to within 25% with the data presented in [3, 6] for asbestos Textolite and fiberglass material with an epoxy binder if the Fo number is obtained from the expression

$$\frac{T^* - T_0}{T_w - T_0} = \mathrm{Fo}. \tag{5}$$

In order to use Eq. (1) for calculating δ_p, besides the coefficient $K\sqrt{a}$, it is necessary to find the time for establishing the self-similar heating regime and to determine the limits of its applicability.

Experimental data (Figs. 2 and 3) show that Eq. (1) can be used up to the time that the quasistationary heating regime, characterized by constant surface temperature, rate of removal and depth of heating of the material, is established. At the time τ_{δ_T}, a constant heating depth is established. For this reason, if the thickness of the material removed from the surface in the time interval from τ_T to τ_V is neglected, the depth of pyrolysis at the time the quasistationary regime is established can be determined from the equation

$$\delta_p \approx \bar{V}_\infty (\tau_{\delta_T} - \tau_v) + \delta_T. \qquad (6)$$

Then, it follows from Eqs. (1) and (6) that

$$\delta_T = K\sqrt{a}(\sqrt{\tau_{\delta_T}} - \sqrt{\tau_\xi}) - \bar{V}_\infty (\tau_{\delta_T} - \tau_v). \qquad (7)$$

Since the time τ_V is 5-10 times smaller than the time $\tau_{\delta T}$ [1] and in the heating time from τ_T to τ_V the average rate of removal of material is approximately two times less than $\bar{V}_\infty$ neglecting the thickness of the material removed over the time from τ_T to τ_V in Eq. (7) results in an error that does not exceed 10%.

In order to determine τ_T, τ_ξ, τ_V, and $\tau_{\delta T}$, as well as in order to check the applicability of Eq. (7), we carried out experiments under conditions of combined radiative—convective heating with a convective heat flux density of 1.05 kW/cm² and two values of radiant heat flux densities, 0.52 and 1.05 kW/cm². We tested samples of nontransparent quartz glass ceramic in heating time intervals from 1 to 60 sec. The softening temperature for the nontransparent quartz glass is ~1500°K [7]. The material, heated to 1500°K, sharply differs in color from the rest of the material, so that measurements of the heating depth are considerably simplified up to $T^* = 1500$°K. The surface temperature of the samples, tested in all three regimes, was practically identical and constituted 2840°K.

As can be seen from Fig. 4, a change in the depth of pyrolysis in the nonstationary heating regime is directly proportional to $\sqrt{\tau}$ in all variants of the tests. In addition, the tangent of the angle of inclination of the straight lines to the abscissa axis is identical and equals 1.24. The quantity $\sqrt{\tau_\xi}$ is directly proportional to the applied heat flux and can be calculated from the equation

$$\sqrt{\tau_\xi} = \sqrt{\tau} - \frac{\delta_p}{K\sqrt{a}}, \qquad (8)$$

which is derived from geometrical relations in Fig. 4.

Calculating τ_T from the expression proposed in [1] for the case of constant heating action agrees well with the experimental values of τ_ξ obtained:

$$\tau_T = \pi\lambda\rho c \frac{(T_w - T_0)^2}{4q_0^2}. \qquad (9)$$

Apparently, in the absence of combustion on the surface, which is characteristic of quartz glass ceramics, the time τ_ξ can be calculated from such an equation.

Substituting the values of T^* and T_W in Eq. (5), it is possible to determine the number Fo, to find the temperature coefficient K from Eq. (2), and then, knowing the experimental value of $K\sqrt{a}$, to determine the coefficient of thermal diffusivity. For nontransparent quartz glass ceramic with a density of 2200 kg/cm³, whose heat capacity according to the data in [8] at $T' = 1600$°K equals 1.3 kJ/kg, a thermal conductivity of 2.15 W/m·K is obtained.

According to [9], for silicon dioxide with a density of 2200 kg/m³, the coefficient of thermal conductivity at a temperature of T' with the radiant components subtracted out equals 2 W/m·K. If it is assumed that in the nontransparent quartz glass ceramic samples, whose porosity did not exceed 5%, and the emissivity equals 0.83, there is no heat transfer due to radiation, then the agreement between the results is quite good.

Since in all heating regimes, the slopes of the straight lines are the same (Fig. 4), and the surface temperature remains constant, it may be concluded that under the conditions being examined for the given material the coefficient of thermal diffusivity does not depend on the form of the heating and heat flux.

As a result of analyzing the experimental data for fiberglass with an epoxy binder and the quartz glass ceramic for heat fluxes ranging from 0.2 to 2.4 kW/cm² with convective, radiative, and combined radiative—convective forms of heating, the functions $\delta_p = f(\tau)$, $\delta_l = f(\tau)$, and $\delta_T = f(\tau)$ were obtained that permitted determining the values of τ_ξ, τ_V, $\tau_{\delta T}$, and the heating depth. The values of τ_V and $\tau_{\delta T}$ obtained are well approximated by the expressions

$$\tau_v = \frac{a}{4V_\infty^2}, \qquad (10)$$

TABLE 1. Comparison of Experimental and Computed Values of the Times τ_ξ, τ_V, and $\tau\delta_T$ and the Heating Depth δ_T for Quartz Glass Ceramic (I — calculation; II — experiment)

$q_c + q_r$, kw/cm^2	τ_ξ, sec		τ_v, sec		τ_{δ_T}, sec		δ_T, mm		V_∞, m/sec
	I	II	I	II	I	II	I	II	II
1,05	0,53	0,7	5,9	3,5	21,0	22,0	2,03	2,0	0,18
1,05+0,52	0,22	0,3	2,43	2,0	9,1	9,0	1,3	1,25	0,28
1,2+1,05	0,1	0,08	1,04	1,0	3,96	4,0	0,84	0,8	0,48

$$\tau_{\delta_T} = \frac{a}{4\bar{V}_\infty^2}\left(\frac{T_w}{T^*}\right)^2 .$$

Substitution of the values of τ_V and $\tau\delta_T$, computed according to Eqs. (10) and (11), into (7) gives a value for the heating depth that differs from the experimental data by not more than 20%.

Table 1 shows a comparison of the experimental data for τ_ξ, τ_V, $\tau\delta_T$ and the heating depth δ_T, obtained for specimens of quartz glass ceramic in the three heating regimes, with their values computed from Eqs. (7), (9)-(11).

Thus, as a result of the experimental investigation of the failure parameters of heat-shielding materials, we have examined the conditions under which it is possible to replace convective heating by radiative heating and we have established that for asbestos, carbon, and fiberglass materials and quartz glass ceramics in the heat fluxes ranging from 0.2 to 2.4 kW/cm^2 with convective, radiative, and combined radiative-convective forms of heating in the nonstationary heating regime the total thickness of the material heated and removed follows a self-similar law. We have demonstrated the basic possibility for determining the coefficient of thermal diffusivity using the self-similar regime method in the presence of removal of mass from the surface of the heat-shielding material. Equations for calculating τ_ξ, τ_V, $\tau\delta_T$, δ_T, and δ_p are proposed.

NOTATION

δ_p, depth of pyrolysis (total depth of material removed from the surface and layer with altered structure); T_w and T^*, temperature of the material surface and the isothermal surface examined; T_0, temperature of the unheated material; K, a temperature coefficient; τ, heating time; τ_ξ, time for establishing the self-similar heat regime; τ_T, τ_V, and $\tau\delta_T$, times for establishing quasistationary temperature values for the surface, rate of removal of material, and heating depth; a, coefficient of thermal diffusivity; Fo, Fourier's number; V_∞, quasistationary value of the rate of removal; δ_T, thickness of the material layer with an altered structure in the quasistationary failure regime; λ, coefficient of thermal conductivity; c, specific heat capacity; ρ, density; q_0, average heat flux density in the time interval from 0 to τ_T less the emission from the surface; T', average temperature of the material, equal to $(T_w+T_0)/2$; δ_l, thickness of the material removed from the surface of the specimen; q_c and q_r, convective and radiant calorimetric heat flux densities; T_w^1, T_w^2, and T_w^3, surface temperature in air and nitrogen flows and with radiative heating; V_c, rate of displacement of the charring front; V_l, rate of displacement of the surface.

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