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MODEL OF THERMAL DESTRUCTION OF MATERIAL SUBJECTED TO ONE-SIDED HEATING

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The article presents a model of destruction establishing a correlation between the temperature field and the rate of destruction of the material.

It was shown in [1, 2] that under conditions of nonsteady heating with linear entrainment of the material, the path traversed by the isotherm in the range of heating time $\tau_T < \tau < \tau_\delta$ can be calculated by the formula

$$\Delta^* = K\sqrt{a}\,(\sqrt{\tau} - \sqrt{\tau_\xi}), \tag{1}$$

and its speed by the expression

$$V_{\Theta^*} = \frac{K\sqrt{a}}{2\sqrt{\tau}}. \tag{2}$$

According to [2], $K \neq 0$ even with $\Theta^* = 1$, it can therefore be seen from (2) that the speed of the isotherm whose temperature is equal to the surface temperature at the instant of onset of linear entrainment may exceed the speed at which the surface itself moves, and that is in contradiction to the generally accepted model of heating.

However, under real conditions the destruction of the material begins before the surface temperature becomes established, and the temperature of the onset of linear entrainment may be substantially lower than its quasisteady value. For instance, linear entrainment of quartz glass ceramics with $(\alpha/c_p)_0 \sim 3.3$ kg/(m²·sec) begins approximately at 2000°K whereas the quasi-steady surface temperature under such conditions of heating is ~2500°K. In the subsonic jet of an electric-arc heater ($(\alpha/c_p)_0 \sim 1.0$ kg/(m²·sec)) the temperature of the onset of entrainment is 200-300°K higher, but the surface temperature attains 2800°K, too [3].

The results of calculations [4] showed that the process of establishing the quasisteady rate of destruction of the surface is not determined by the nature of flow in the film of melt but basically by the temperature distribution inside the solid. It follows from (2) that the speed of the isotherm corresponding to the temperature of the onset of entrainment of mass from the surface decreases from the instant τ_y within the time τ_V in proportion to $1/\sqrt{\tau}$. On the other hand, the rate of destruction of the surface in that period increases from 0 to V_∞. Assuming that the temperature field determines the nature of the change of the rate of entrainment, we represent the process in question in the form of a diagram (Fig. 1).

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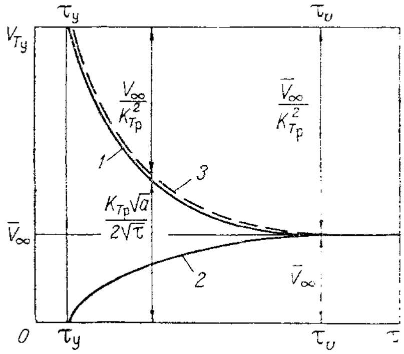

Fig. 1. Diagram of the change of speeds of the isotherm corresponding to the temperature of onset of linear entrainment and of the surface: 1) speed of the isotherm; 2) speed of the surface; 3) speed of the surface with a view to the scale factor $1/K^2_{T_p}$.

On the basis of the processing of the expermental results by (1), the authors of [2] suggested the value of the factor K_{T_p} for an isotherm with $\Theta^* \approx 1$. We assume that the correlation of the speeds of the isotherm corresponding to the temperature of the onset of entrainment and of the surface is also established with the aid of the factor in question. Then, as can be seen from Fig. 1, the speed of the isotherm at the instant τ_y is determined by the expression

$$V_{T_y}(\tau_y) = \frac{K_{T_p}\sqrt{a}}{2\sqrt{\tau}} + \frac{V_\infty(\tau)}{K^2_{T_p}} = \bar{V}_\infty + \frac{\bar{V}_\infty}{K^2_{T_p}}. \tag{3}$$

Dependence (3) presupposes that the reduction of the speed of the isotherm is accompanied by a corresponding increase of the rate of destruction of the surface which repeats mirror-like the regularity of the change of V_{T_y} with the scale factor $1/K^2_{T_p}$.

From (3) we find that

$$V_\infty(\tau) = (K^2_{T_p} + 1)\bar{V}_\infty - \frac{K^3_{T_p}\sqrt{a}}{2\sqrt{\tau}}, \tag{4}$$

hence for $V_\infty = 0$ we obtain the formula for calculating the time of onset of mass entrainment from the surface

$$\tau_y = \frac{K^6_{T_p}a}{4(K^2_{T_p} + 1)^2\bar{V}^2_\infty}. \tag{5}$$

At the instant $\tau = \tau_v$ the speed of the isotherm is equal to $\bar{V}_\infty$, consequently we obtain from (2) that

$$\tau_v = \frac{K^2_{T_p}a}{4\bar{V}^2_\infty}. \tag{6}$$

Thus relation (4) makes it possible to calculate the change of speed V_∞ in the period of time from τ_y to τ_v with constant supplied heat flux. The times τ_y and τ_v are determined by (5) and (6). During that period the speed with which the surface moves increases from 0 to $\bar{V}_\infty$, i.e., there is a gradual increase of the proportion of heat absorbed on account of the thermal effects of phase and physicochemical transformations. It was suggested in [5, 6] to examine the mean integral heat flux together with the heat flux in quasisteady regime, and with its aid to evaluate the rate of destruction of the material. In our case we introduce the notion of the mean integral speed of entrainment in the period of time from τ_y to τ_v and we will prove that

$$\frac{V^{\mathrm{av}}_\infty}{\bar{V}_\infty} = K_{T_p}. \tag{7}$$

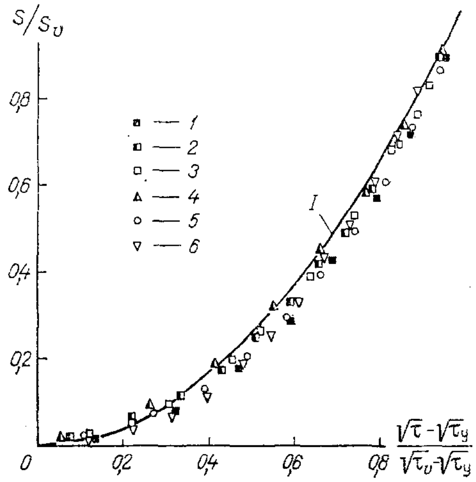

Fig. 2. Change of linear entrainment of quartz glass, of pure and of doped quartz glass ceramics in the range of heating times from τ_y to τ_v: I) calculation by (16); dots: experiment [1) doped, 2, 4) pure glass ceramics; 3, 5, 6) quartz glass; 6) data of [7]].

Integrating (4), we find the expression for calculating the path traversed by the surface in the time interval from τ_y to τ_v:

$$S(\tau) = (K_{T_p}^2 + 1)\bar{V}_\infty(\tau - \tau_y) - K_{T_p}^3 \sqrt{a}\,(\sqrt{\tau} - \sqrt{\tau_y}) \quad (8)$$

and the mean integral speed

$$V_\infty^{av} = \frac{(K_{T_p}^2 + 1)\bar{V}_\infty(\tau_v - \tau_y) - K_{T_p}^3 \sqrt{a}\,(\sqrt{\tau_v} - \sqrt{\tau_y})}{\tau_v - \tau_y}. \quad (9)$$

Solving (5), (6), (9) jointly, we arrive at (7) and obtain

$$2K_{T_p}^3 - K_{T_p}^2 + K_{T_p} - 1 = 0,$$

and hence $K_{T_p} \approx 0.74$, i.e., K_{T_p} is the constant of destruction correlating the process of destruction of the surface of the material with its temperature field [2].

In deriving Eq. (4) it was assumed that the surface temperature is established at the instant τ_T which coincides with τ_y, and the time τ_T can be calculated by a dependence obtained in [4] for the case when the supplied heat flux q = const:

$$\tau_T = \pi\lambda\rho c\,\frac{(T_w - T_0)^2}{4q^2}. \quad (10)$$

Since the supplied flux changes within time τ_T, we substitute into (10) its mean integral value [5]. Then, equating (5) and (10), we obtain a dependence for evaluating the speed of entrainment in quasisteady regime of destruction found in [6]:

$$\bar{V}_\infty = \frac{K_{T_p}^3}{\sqrt{\pi}(1 + K_{T_p}^2)}\,\frac{q_{av}}{\rho c(T_w - T_0)} = \frac{q_{av}}{6{,}79\rho c\,(T_w - T_0)} \quad (11)$$

When we substitute (5) and (6) into (1) and (8) we find that at the instant that the quasisteady rate of destruction is established, the path traversed by the surface is determined by the formula

$$S_v = \frac{K_{T_p}^2}{K_{T_p}^2 + 1}\,\frac{a}{4\bar{V}_\infty}, \quad (12)$$

and the path traversed by the isotherm corresponding to the temperature of onset of mass entrainment from the surface is determined by the expression

$$\Delta_{T_y} = \frac{K_{T_p}^2}{K_{T_p}^2 + 1}\,\frac{a}{2\bar{V}_\infty}. \quad (13)$$

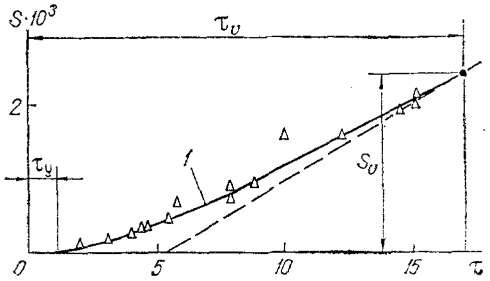

Fig. 3. Change of linear entrainment of quartz glass in the range of heating times from τ_y to τ_v with heat flux of 7650 kW/m²: 1) calculation by (16); dots: experiment. S, m; τ, sec.

Hence it can be seen that with the adopted assumptions the ratio of the path traversed by the isotherm T_y to the path traversed by the surface does not depend on the thermal diffusivity or on the speed V_∞ with which the surface moves, and it is equal to 2.

It is interesting to note that the results of the calculations of [4] for an isotherm with $\Theta^* = 0.1$ also show that in the entire range of numbers m under consideration the thickness of the entrained layer $S(\tau_\delta)$ amounts to slightly more than half the corresponding value of the total thickness $\Delta^*(\tau_\delta)$.

The time of establishing the quasisteady value of the depth of heating can be calculated by a formula obtained from (2):

$$\tau_\delta = \frac{K^2 a}{4V_\infty^2}, \tag{14}$$

where K is determined by a dependence presented in [2]:

$$K = -\frac{1}{K_{T_p}^2}\Theta^* + \frac{K_{T_p}^2}{1 - K_{T_p}}. \tag{15}$$

The simple theoretical dependences presented above cannot encompass the entire variety of factors affecting the process of high-temperature destruction of materials. However, in many cases they yield perfectly satisfactory agreement with experimental results. In particular, it was shown in [6] that dependence (11) is applicable in the evaluation of the quasisteady rate of destruction, and in [2] it was shown that expressions (1) and (15) are applicable in the calculation of the temperature field inside material in the process of destruction.

It can be seen from Fig. 2 that in the range of heating times from τ_y to τ_v the experimental values of linear entrainment in the destruction of quartz glass, of pure and doped quartz glass ceramics under the effect of a constant heat flux are satisfactorily described by the dependence

$$\frac{S}{S_v} = \left(\frac{\sqrt{\tau} - \sqrt{\tau_y}}{\sqrt{\tau_v} - \sqrt{\tau_y}}\right)^2. \tag{16}$$

According to expression (16) we processed the results obtained in the present work (see, e.g., Fig. 3) and the data of [7].

Differentiating (16) we find

$$\frac{dS}{d\tau} = V_\infty = \frac{\sqrt{\tau} - \sqrt{\tau_y}}{\sqrt{\tau}\,(\sqrt{\tau_v} - \sqrt{\tau_y})^2} S_v. \tag{17}$$

When, we substitute relations (5), (6), (12) into (16) and (17), we obtain the equations for the path and speed of the surface (8) and (4). Hence follows that (4) and (8) describes satisfactorily the process of nonsteady destruction of the surface of the material.

NOTATION

τ, heating time; τ_T, τ_V, τ_δ, times of establishing the quasisteady values of the surface temperature, speed and depth of heating, respectively; τ_y, time of onset of linear entrainment;

Δ^*, path traversed by the isotherm under consideration, measured from the fixed surface; τ_ξ, time determining the reference point of intersection of the dependence of the path traversed by the isotherm under consideration with the axis of abscissas; K, temperature coefficient; a, thermal diffusivity; $\Theta^* = (T^* - T_0)/(T_w - T_0)$, where T_w, T^*, are the temperatures of the surface of the material and of the isotherm under consideration, respectively; T_0, temperature of the unheated material; τ_y, temperature of the onset of linear entrainment; V_∞, V_{Θ^*}, speeds with which the outer surface and the isotherm, respectively, move; $\bar{V}_\infty$, quasisteady speed with which the surface moves; $V_{T_y}(\tau_y)$, speed of the isotherm corresponding to the temperature of onset of linear entrainment at the instant τ_y; $(\alpha/c_p)_0$, heat-transfer coefficient; K_{T_p}, constant of destruction of the material; q, supplied heat flux; q'_{av}, mean integral heat flux in the time from 0 to τ_T; λ, thermal conductivity; ρ, density; c, heat capacity; S, linear entrainment; S_y, linear entrainment at the instant τ_y.

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STUDY OF THE PARAMETERS OF A TWO-PHASE JET AND ITS EFFECT ON A BARRIER

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Experimental and theoretical results are presented from a study of the parameters of a high-temperature two-phase jet and its thermal effect on a nonpermeable surface.

The intensive development of technology is associated with an increase in the thermodynamic parameters of the working parts of various devices and, as a rule, with the action of high-temperature multiphase flows (gas—solid-particle and gas—liquid-particle systems, etc.) on the material of structural elements of turbines, rocket engines, plasma chemical reactors, and other power plants operating in high-speed two-phase flows.

In connection with this, it is of great practical interest to study the parameters of two-phase, high-temperature, high-speed flows and their thermal effect on an impermeable surface with different angles of incidence.

To conduct experimental studies, we developed a stand (Fig. 1) which includes an electric-arc gas heater (plasmatron) 1 with a linear design and a nozzle 28 mm in diameter, a batching device for the powdered materials 2, a system 4 to insert and remove the baffle 5 in front of the 40-mm-diameter model 6, an ISSO-1 rate meter 3, an RFK-5 photographic recorder 8, and an EOP-66 pyrometer 9.

The linear plasmatron is distinguished from other types of arc heaters by the simplicity of its design and the convenience of its use. The plasmatron was described in detail in [1] along with results of study of its thermal and electrical characteristics for air, nitrogen, and carbon dioxide.

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