8. Ya. M. Gumnitskii, V. I. Krivosheev, and G. A. Aksel'rud, Zh. Prikl. Khim., 55, No. 4, 837-841 (1982).
9. D. A. Frank-Kamenetskii, Diffusion and Heat Transfer in Chemical Kinetics, Plenum Publ. (1969).
10. A. I. Dubynin, "Investigation of mass transfer in a solid-liquid system complicated by gas release," Candidate's Dissertation, Technical Sciences, Lvov (1974).

DETERMINATION OF THE THERMAL STATE OF MATERIAL SUBJECTED TO EROSIVE DEGRADATION

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The experimental data are generalized and governing parameters and analytic relations for estimating the thermal state of material subjected to the thermo-erosive action of a dusty gas flow are proposed. Comparison of the results of numerical calculations obtained using the method described in [1] with estimates based on the relations proposed gives the error of the latter.

When a high-velocity two-phase flow acts on a target material, the temperature field in the latter changes periodically as it is progressively eroded by particle impact [1]. The presence of condensed particles in the flow, on the one hand, intensifies the convective heat transfer between the gas and the wall and, on the other, discretely reduces the thermal energy stored in the wall material as a result of removal of the heated surface layer. Depending on the velocity V_{pw} and the size of d_p of the particles striking the wall and on the time between successive impacts τ_{er} the relation between the thermal energies supplied and stored varies widely, which seriously complicates the estimation of the thermal state of wall. The problem becomes even more complex if one takes into account the fact that, as a rule, the thickness of the eroded surface layer δ_{er} (depth of crater) increases considerably with increase in wall temperature [2].

As distinct from thermochemical degradation, the erosion mechanism depends on breakage of the wall material over a considerable depth, commensurable with the size of the impacting particle d_p. Accordingly, layers of material at different temperatures and hence with different bond rupture energies take part in the process. For a nonuniform temperature distribution within the wall material as the leading parameter it is possible to select the mean-integral temperature over the crater depth δ_{er}:

$$T_s = \frac{1}{\delta_{er}} \int\limits_0^{\delta_{er}} T(y)\,dy.$$

For a quasisteady wall erosion regime, when the temperature profile has an exponential form [3], the mean-integral temperature is related to the thermophysical parameters of the material (ρ_M, c_M, λ_M) and the erosion rate by the expression

$$\frac{T_s - T_0}{T_w - T_0} = \frac{\lambda_M}{c_M \delta_{er} G_\Sigma}\left[1 - \exp\left(-\frac{c_M \delta_{er} G_\Sigma}{\lambda_M}\right)\right], \qquad (1)$$

where $G_\Sigma = G_T + G_{er}$. However, a quasisteady regime is established only when the temperature-profile relaxation time τ_T is less than the characteristic time τ_{er}. The relaxation time

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depends on the temperature level from which heating of the surface layer begins, the rate of convective heat transfer in the two-phase flow, the temperature, the rate of thermochemical degradation, and the thermophysical properties of the wall material. As a first approximation it is possible to use the relation of classical heat conduction theory for the time required to establish the temperature T_w in a semiinfinite body in the presence of a constant heat flux q_w:

$$\tau_\text{т} = \frac{\pi}{4} \frac{\lambda_\text{м} c_\text{м} \rho_\text{м}}{q_w^2} (T_w - T_0)^2.$$

In the general case, instead of the initial temperature T_0 it is possible to use a certain characteristics value T_{1-s} corresponding to the residual heat in the material after removal of a surface layer of depth δ_{er}.

For quasisteady degradation the depth of the heated layer will be the less the higher the mass transfer rate:

$$\delta_\text{т} = \frac{a_\text{м}}{V_\text{м}} \ln\left(\frac{T_w - T_0}{T_\delta - T_0}\right) = \frac{\lambda_\text{м}}{c_\text{м} G_\Sigma} \ln\left(\frac{T_w - T_0}{T_\delta - T_0}\right).$$

Here, T_δ denotes the assumed lower temperature limit of the heated layer. In this case the quasisteady regime sets in at a crater depth δ_{er} small as compared with δ_T. However, when the crater depth is commensurable with the depth of the heated layer, and $\tau_{er} < \tau_T$, for determining δ_T it is possible to use the expression for the heating of a nondegradable wall surface in time τ_{er} with the initial condition $T(y) = T_0$:

$$\delta_\text{т} = k \sqrt{a_\text{м} \tau_\text{er}}, \quad \text{where} \quad k \approx 2{,}0.$$

The effective time interval between successive particle impacts τ_{er} is related to the particle mass flux density G_p and the crater depth δ_{er} or the erosive degradation rate G_{er} [2]:

$$\frac{\tau_\text{er}}{d_p} = \sqrt[3]{\frac{1}{4} \frac{\rho_p \rho_\text{м}^2}{G_p G_\text{er}^2}},$$

$$\frac{\delta_\text{er}}{d_p} = \sqrt[3]{\frac{1}{4} \frac{\rho_p}{\rho_\text{м}} \overline{\overline{G}}} = \sqrt[3]{\frac{1}{8} \frac{\rho_p}{\rho_\text{м}} \frac{V_{pw}^2}{H_\text{er}}}.$$

The effective erosive degradation enthalpy H_{er}, the kinetic energy of the particles expended on destroying unit mass of the material investigated, is determined by the intensity of erosive degradation $\overline{\overline{G}}$ [4]:

$$H_\text{er} = V_{pw}^2 / 2\overline{\overline{G}}, \quad \overline{\overline{G}} = G_\text{er} / G_p.$$

In [1] it was shown that in the dimensionless coordinates $(\delta_{er}/\delta_T) - (\tau_r/\tau_{er})$ the entire range of wall thermal regimes can be divided into two regions. In one of these the erosive degradation process G_{er} predominates, so that the thermochemical mass transfer component G_T can be neglected. Such a situation arises, in particular, when $\tau_{er} < \tau_T$, and $\delta_{er} > \delta_T$. In the other region the thermoerosive degradation components G_{er} and G_T are commensurable.

The boundary between these two regions is a curve that approximates the hyperbola xy = const. This result can be used as a basis for formulating the new dimensionless number

$$E = \frac{\delta_\text{er}}{\delta_\text{т}} \frac{\tau_\text{т}}{\tau_\text{er}} = \left[\frac{G_p V_{pw}^2}{2 q_w}\right]^2 \times$$

$$\times \left[\frac{c_\text{м} (T_w - T_{1-s}) + \Delta Q_w + \Gamma\gamma (I_e - I_w)}{H_\text{er}}\right]^2 \left[\frac{G_\text{т}}{G_\text{er}} + 1\right] =$$

$$= \left\{\frac{G_\text{er} [c_\text{м} (T_w - T_{1-s}) + \Delta Q_w + \Gamma\gamma (I_e - I_w)]}{q_w}\right\}^2 \left[\frac{G_\text{т}}{G_\text{er}} + 1\right]$$

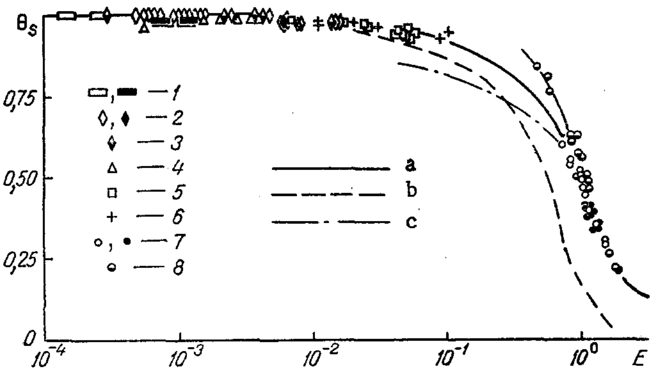

Fig. 1. Dimensionless mean-integral temperature of the surface layer as a function of the E number; (a) experimental data processed by least squares $\Theta_s = \exp[-(0.77 \cdot E)^{1.52}]$; (b) in accordance with the relations for quasisteady heating of the wall Θ_s^{st}; (c) from the analytic solutions of the differential equation of heat conduction Θ_s^{ast}; the points represents the results of processing the experimental data in accordance with the numerical method of [1]: 1) copper; 2, 3) stainless steel; 4) graphite; 5) titanium; 6) carbon-carbon composite; 7, 8) glass-reinforced plastic; 1, 2, 4, 6, 7) data obtained by varying G_p; 3, 5, 8) by varying T_0'; white and black-and-white symbols: $P_0'/P_{00} \approx 0.175$; black symbols ≈ 0.4.

or in the absence of thermochemical mass transfer

$$E = \left[\frac{G_p V_{pw}^2}{2q_w}\right]^2 \left[\frac{c_M (T_w - T_{1-s})}{H_{er}}\right]^2 = \left[\frac{G_{er} c_M (T_w - T_{1-s})}{H_{er}}\right]^2.$$

From these expressions it follows that the E number is the ratio of the amount of thermal energy of an eroded surface layer of thickness δ_{er} dissipated as a result of erosive degradation to the amount of thermal energy accumulated in a heated layer of thickness δ_T. The net specific energy release of the surface processes ΔQ_w and the gasification fraction Γ are determined from the "purely thermochemical" interaction of the wall material and the high-temperature gas flow, and the injection coefficient γ in the two-phase flow is estimated as $\gamma_T = 0.2$ for a turbulent boundary layer.

The E number is a number of the energy type, which follows clearly from the simplified form which applies when the thickness of the eroded layer exceeds the thickness of the heated layer ($\delta_{er} \geq \delta_T$) and, consequently, there is no residual heat left in the material after removal of a layer $\delta_{er}(T_{1-s} = T_0)$:

$$E = \left[\frac{G_p V_{pw}^2}{2q_w}\right]^2 \left[\frac{H_{ef}}{H_{er}}\right]^2 \left[\frac{G_T}{G_{er}} + 1\right].$$

In fact, the E number establishes a "threshold" between the regions of existence of the erosive and thermoerosive wall degradation mechanisms. When $E > E^* \approx 1$ it is possible to neglect the thermochemical component of the overall mass transfer rate. As shown below, the significance of the E number is not confined to the simple statement of a qualitative fact but also finds expression in quantitative estimates of the thermal state of the material in the presence of combined thermoerosive action of the flow.

In Fig. 1 the numerous experimental data, including those of [2, 5], processed by the method described in [1], have been generalized in the form of a unified dependence of the dimensionless mean-integral temperature Θ_s on the E number:

$$\Theta_s = \frac{T_s - T_0}{T_w - T_0} = \exp[-(0{,}77E)^{1{,}52}].$$

Metals operating in a gasdynamic environment are characterized by a low value of the E number and similar values of T_s and T_w: $T_s \approx T_w$. For glass-reinforced plastics some differentiation of the $T_s(E)$ and $T_w(E)$ curves is observed, the surface temperature T_w reaching the thermal degradation temperature $T_{t.d}$ right up to the critical value $E^* \approx 1$, which coincides with the theoretical estimates of [1]. The value E^* divides Fig. 1 into two regions, characterized by the thermoerosive ($E < E^*$) and erosive ($E \geq E^*$) degradation mechanisms respectively. Moreover, the region near the critical value of the E number determines the relation between the parameters of the wall material and the free-stream parameters for which the latter (G_p, V_{pw}, d_p, q_w) have the strongest influence on the thermal state of the surface layer.

Apart from the numerical method described in [1], in some cases for estimating the thermal state of the wall surface it is possible to use simpler analytic relations. Firstly, the temperature profile and the quantities T_s and T_w are calculated from the relations for the quasisteady heating of a wall degraded at a constant mass transfer rate, where the mean-integral temperature T_s^{st} is determined from expression (1) and the surface temperature from the energy balance in the eroded layer:

$$(\alpha/c_p)(I_e - I_w) + fG_pV_{pw}^2/2 = \varepsilon\sigma\,[T_w^{st}]^4 + G_\Sigma c_M\,(T_s^{st} - T_0) + G_T\,[\Delta Q_w + \Gamma\gamma\,(I_e - I_w)].$$

Secondly, the heating in the absence of erosion between particle impacts on the interval τ_{er} is calculated from the known analytic solutions of the differential heat-conduction equation for constant initial $T(y) = T_0 = \text{const}$ and boundary $(\alpha/c_p) = \text{const}$ conditions:

$$\frac{T_s^{ast} - T_0'}{T_0 - T_0'} = \frac{1}{\mathrm{Bi}}\left\{\exp(\mathrm{Bi} + \mathrm{Bi}^2\,\mathrm{Fo})\left[1 - \operatorname{erfc}\left(\frac{1}{2\sqrt{\mathrm{Fo}}} + \mathrm{Bi}\sqrt{\mathrm{Fo}}\right)\right] + \right.$$

$$\left. + \exp(\mathrm{Bi}^2\,\mathrm{Fo})(\operatorname{erfc}\mathrm{Bi}\sqrt{\mathrm{Fo}} - 1) + (\mathrm{Bi} + 1)\left(\operatorname{erfc}\frac{1}{2\sqrt{\mathrm{Fo}}} - 1\right) - \frac{2\,\mathrm{Bi}\sqrt{\mathrm{Fo}}}{\sqrt{\pi}}\left[\exp\left(-\frac{1}{4\,\mathrm{Fo}}\right) - 1\right]\right\},$$

$$\frac{T_w^{ast} - T_0'}{T_0 - T_0'} = \exp(\mathrm{Bi}^2\,\mathrm{Fo})\operatorname{erfc}\mathrm{Bi}\sqrt{\mathrm{Fo}}.$$

Here, the Biot number $\mathrm{Bi} = \alpha\delta_{er}/\lambda_M$ and the Fourier number $\mathrm{Fo} = a_M\tau_{er}/\delta_{er}^2$ are determined from the depth of the crater δ_{er} and the interval between particle impacts τ_{er}.

In Fig. 1 we have plotted the values Θ_s^{st} and Θ_s^{ast} calculated by these two methods. For values of $E < 0.1$ (for metals) the results of calculating T_s^{st} from the expressions for the quasisteady degradation regime give a deviation of up to 15% from those obtained using the numerical method of [1]. In the case of composite materials the deviation increases as their thermal diffusivity and erosion resistance decrease (for glass-reinforced plastics at $E^* \approx 1$ it is already 60%). However, for these materials the layer removed by a particle δ_{er} is similar in thickness to the heated layer δ_T. Therefore after removal the surface temperature differs little from the initial value T_0. This makes it possible to calculate the heating of the surface layer impacts in the absence of erosion by the second method, which gives results that coincide with the results of calculations based on the numerical method of [1] for $E \geq 1$. When $E < 1$ and residual heat accumulates in the surface layer, the deviation of T_s^{ast} from T_s increases and reaches 12-15% at $E \approx 0.5$.

An analysis of the dependence $\Theta_s(E)$ reveals that the heat flux to the wall, the particle concentration in the flow and the particle impact rate have an obvious effect on the mean temperature of the surface layer. Therefore, by assigning various values of these parameters it is possible to vary T_s in the experimental investigation of the dependence of the erosion resistance of materials on their temperature in a gasdynamic environment. However, the effect of the particle size on the E number and hence on T_s requires clarification. The fact is that for a constant particle mass concentration in the flow as d_p increases so do the crater depth δ_{er} and the time interval τ_{er} (2) during which heating of the wall surface takes place, i.e., in this case deeper penetration of the particles into the cold layers of the material and deeper heating of the latter have a directly opposite effect on T_s.

The effect of particle size in the interval 5-500 µm on the thermal state of materials subjected to thermoerosive action is calculated parametrically from the corresponding analytic

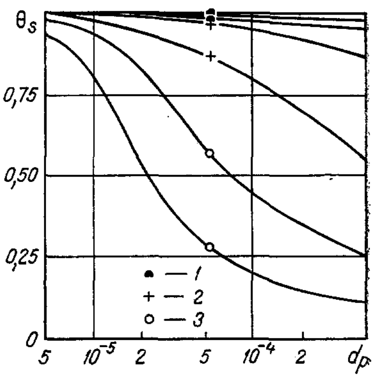

Fig. 2. Effect of particle size d_p, m, on the dimensionless mean-integral temperature of the surface layer of material: 1) stainless steel; 2) carbon–carbon composite; 3) glass-reinforced plastic (experimental data); the curves represent the results of the calculations.

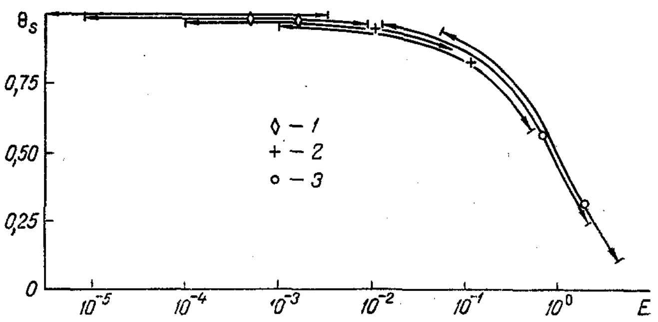

Fig. 3. Dimensionless mean-integral temperature of the surface layer of material as a function of the E number with variation of the particle size: 1) stainless steel; 2) carbon–carbon composite; 3) glass-reinforced plastic; 1-3) experimental data for $d_p \approx 50$ μm; the arrows indicate the ranges of variation of Θ_s and E as d_p is varied on the interval 5-500 μm.

relations on the assumption that there are no scale effects, i.e., there is no effect of particle size on the erosion of the material associated with its structural characteristics. For calculation purposes we took the experimental data ($d_p \approx 50$ μm) for stainless steel ($E = 5 \cdot 10^{-4}$; $1.4 \cdot 10^{-3}$); carbon–carbon composite ($E = 10^{-2}$; 10^{-1}), and glass-reinforced plastic ($E = 0.76$, 1.67). The dependence of Θ_s on d_p obtained as a result of the calculations (see Fig. 2) can be reduced to a unified curve by using the E number (see Fig. 3). The particle size, like the previously mentioned flow parameters, has an important influence on the thermal state of the wall material in the region of the critical value $E^* \approx 1$. For glass-reinforced plastic, characterized under the conditions in question by low values of the Fourier number, the time required to establish a surface temperature close to the temperature at which particle impact takes place τ_T is much less than the interval τ_{er}. Therefore an increase in τ_{er} with increase in d_p (2) does not have much effect on the temperature T_s, which mainly depends on $\delta_{er} \sim d_p$. For metals these times are commensurable; as d_p is varied, the effect of the crater depth and the interval between impacts on the temperature T_s balance each other out.

NOTATION

T, temperature; P, pressure; Θ, dimensionless temperature; ρ, density; c, specific heat; λ, thermal conductivity; a, thermal diffusivity; d, diameter; G, mass flux density; $\overline{\overline{G}}$, intensity of erosive degradation; H, the effective degradation enthalpy; I, gas enthalpy; V, velocity; δ, thickness; τ, time; q, heat flux; α, heat-transfer coefficient; f, particle kinetic energy accommodation coefficient; ε, emissivity; σ, Stefan—Boltzmann constant; ΔQ, specific energy release of the processes of fusion, vaporization, etc. of the material; Bi, Biot number; Fo, Fourier number; E, a dimensionless number representing the thermal state of material subjected to thermoerosive action; y, coordinate perpendicular to the wall surface. Indices: 0, initial; w, surface; s, mean-integral; M, wall material; p, particle; Σ, sum; 00, total; T, thermal, turbulent; ef, thermochemical; er, erosion; e, edge of boundary layer; st, calculation based on relations for the quasisteady degradation regime; ast, calculation based on analytic solutions of the heat-conduction equation; *, critical value; ', stagnation parameter.

LITERATURE CITED

1. A. V. Vasin and Yu. V. Polezhaev, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 1, 120-126 (1984).
2. A. V. Vasin, D. S. Mikhatulin, and Yu. V. Polezhaev, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 6, 172-175 (1985).
3. Yu. V. Polezhaev and F. B. Yurevich, Heat Shielding [in Russian], Moscow (1976).
4. Yu. V. Polezhaev, V. P. Romanchenkov, I. V. Chirkov, and V. N. Shebeko, Inzh.-Fiz. Zh., 37, No. 3, 395-404 (1979).
5. D. S. Mikhatulin and Yu. V. Polezhaev, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 4, 92-98 (1986).

SOME QUESTIONS IN THE THEORY AND DESIGN OF EXPLOSIVE PLASMA GENERATORS

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Methods are presented for calculation of the thermophysical parameters of the plasma produced by operation of explosive plasma generators and for the design of such generators.

The method of producing high temperature dense plasma using gas impermeable plates which collide at a small angle, i.e., under acute angle geometry conditions, is widely known [1]. Explosive plasma generators which realize this method have found practical application [2-5]. The most widely used is the generator in which collision of a plane plate with the internal surface of a hollow hemisphere is used [3-5].

Observation of processes occuring in this accute angle geometry is difficult, so that they remain insufficiently studied. As a result, design of generators for plasma production with prespecified parameter values is impossible, and it is difficult to estimate the parameters of plasmas produced by existing generator constructions [2].

An infinite number of explosive generator configurations is theoretically possible, although the authors are aware of only several actual construction techniques. To form an overall picture of the given problem it is desirable to consider the gas dynamic processes which occur in the acute angle geometry, and obtain the expressions which relate the final parameters of the compressed gas to the properties of the colliding bodies and their relative velocities. After deriving such relationships it becomes possible to solve problems of explosive plasma generator design. Therefore the goal of the present study is to derive such relationships and analyze possible methods of increasing plasma temperature.

We will consider the compression of a gas included between two infinite parallel plates A and B, which beginning at time $t_0 = 0$ approach each other, moving with identical velocities v, exceeding the speed of sound a_0 in the unperturbed gas. Let P_0, ρ_0, T_0 be the pressure,

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