FRACTURE CHARACTERISTICS OF GLASS-GRAPHITE BODIES IN A PARTIALLY IONIZED AIR FLOW

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The accuracy of computations of the fracture characteristics of glass-graphite materials is estimated by using the analogy between the heat and mass transfer in a partially ionized boundary layer.

Formulation of the Problem

There is a significant quantity of papers in the literature that are devoted to an analysis of the processes proceeding during the fracture of glass-graphite bodies in high-temperature gas flows [1-3]. However, detailed examination of the processes within the bulk of the material being fractured is carried out in the papers mentioned in isolation from the processes proceeding in the boundary layer. The interaction of the gas medium with the surface layers of the material is described by using an approximate method based on the analogy between the heat and mass transfer (HMT). In this connection, the solution of the adjoint HMT problem in the bulk of the material and in the shock layer being formed at the surface during a high-temperature flow over it is of practical interest.

The fundamental parameters characterizing the process of mass entrainment for glass-graphite solids obtained in the numerical solution of the conjugate problem of aerothermochemical fracture, andbecause of application of an approximate method of computing the heat and mass transfer in the boundary layer, are compared in the present investigation. In analyzing the results special attention is paid to those material fracture conditions that correspond to the development of the ionization of the incoming gas stream. The regularities of the conjugate HMT are investigated for the following fracture mechanisms of glass-graphite materials whose models are elucidated in [1-3].

1. The fracture mechanism of homogeneous quartz glass (mechanism I). Here the mass rate of material entrainment is identified with the mass rate of entrainment of the melted quartz.

2. The scheme of "mechanical entrainment of carbon" (mechanism II). In contrast to the preceding model, a composite glass-graphite material is considered. When using mechanism II, the heterogeneous chemical interaction between glass and carbon can be neglected in the internal layers of the material. Moreover, it is assumed that carbon is mechanically pulled down into the film of SiO_2 melt and the gaseous pyrolysis products of the binder are blown completely into the boundary layer.

3. The mechanism of "surface burnup of carbon" (mechanism III). In investigating this model it is considered that the carbon carcass is hard enough so as to withstand the internal temperature stresses and shear forces from the incoming gas flow. Moreover, it is assumed that $\Gamma_{c,w} = 1$. Therefore models II and III describe the limit cases of carbon behavior during entrainment of the material mass.

4. The mechanism of "differentiated burnup of carbon" (mechanism IV). The distinction between this model and model III is that here, in addition to the surface burnup of carbon, the entrainment of its mass due to the passage of the heterogeneous chemical interaction between C and SiO_2 in the internal layers of the coating is also taken into account.

Analysis of the material fracture mechanisms is carried out in the following parameters: the temperature of the surface being heated, T_w, °K; the dimensionless rate of injection of the vapor of fracturing material into the boundary layer, $\overline{G}_{\Sigma,w}$; the silicon dioxide gasification factor $\Gamma_{SiO_2, \Sigma}$; and the effective enthalpy of the material, J_{ef}, J/kg.

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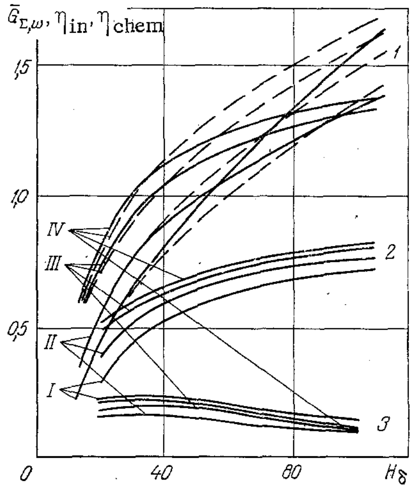

Fig. 1. Dimensionless gasification rate (1), contribution of the effect of injection (2), and chemical reactions on the surface (3) to the total heat flux to the surface for $p_e = 10^5$ Pa, R = 0.1 m. Roman numerals on the curves denote the fracture mechanism. Solid curves are the result of solving the adjoint problem; dashes are solution by using the HMT analogy. H_δ, mJ/kg.

To obtain the required results, the problem was solved twice in each version of the computation: first the adjoint problem of aerothermochemical fracture of the material, and then by using an approximate method of computing the HMT in the boundary layer. The following mass contents of the components [4] were used in the computations: $\varphi_{SiO_2} = 0.7$; $\varphi_C = 0.23$; $\varphi_H = 0.02$; $\varphi_O = 0.05$.

The adjoint HMT problem was considered in the quasistationary formulation. A system of equations describing the hypersonic flow around the forward stagnation point of a blunt body by a high-temperature viscous and heat conducting gas flow in the region between the detached shock and the body surface [5, 6] was used to investigate the processes in the gas phase. It is assumed that ambipolar diffusion holds in the major part of the compressed layer, there is no electrical current to the wall, and the effects of thermo- and barodiffusion are negligible. The chemical reactions in the boundary layer were considered "frozen," and "equilibrium" on the outer boundary of the shock layer and at the body surface. The system of equations of motion, energy conservation, and also the diffusion and Stefan–Maxwell equations were solved by the method of quasilinearization [7]. A computation of concentration diffusion was performed by using the method in [8], and hence the diffusion transfer of 32 components was taken into account: H, H_2, C, N, O, OH, H_2O, C_2, C_2H, C_2H_2, CN, HCN, CO, N_2, Si, SiH, NO, O_2, C_3, SiC, SiO, CO_2, Si_2C, C_2N_2, Si_2, SiO_2, SiC_2, H^+, C^+, N^+, O^+, e^-.

The transfer coefficients and thermophysical functions of the multicomponent partially ionized gas mixture were calculated by the method in [9].

To describe the body fracture mechanism, an assumption was introduced that the material is an isotropic mechanical mixture of thermally stable glass (SiO_2) and an organic binder into whose composition the chemical elements H, C, N, O, Si enter. The process of thermal destruction of such material was described in conformity with [1-3].

Computation of the boundary layer by the approximate method in [4] included assigning the function for the attenuation of the convective thermal flux q_k in the form

$$\psi_q = \frac{\alpha/c_p}{(\alpha/c_p)_0} = \frac{1}{3(\gamma\bar{G}_{\Sigma,w})^2 + \gamma\bar{G}_{\Sigma,w} + 1}, \tag{1}$$

where

$$\alpha/c_p = q_k/(H_\delta - H_w);\ \gamma = 0.6;\ \bar{G}_{\Sigma,w} = G_{\Sigma,w}/(\alpha/c_p)_0.$$

The quantity $(\alpha/c_p)_0$ was calculated in the solution of the problem of an ideal flow of partially ionized air around a catalytic nondestroyed surface under conditions corresponding to the flow around a destroyable body.

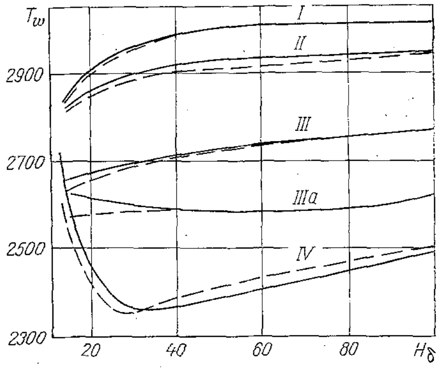

Fig. 2. Temperature of the heated surface for $p_e = 10^5$ Pa, R = 0.1 m; III*a* – results of a computation for $p_e = 10^5$ Pa, R = 1 m; see Fig. 1 for remaining notation. T, °K.

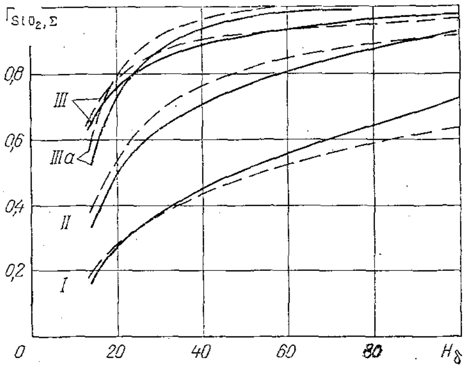

Fig. 3. Silicon dioxide gasification factor. See notation in Figs. 1 and 2.

Attenuation of the friction stress gradient was given in the form

$$\psi_\tau = \tau_{w,x}/\tau_{w,x,0} = \psi_q, \tag{2}$$

where $\tau_{w,x} = 1.7\,(\alpha/c_p)\, du_e/dx$.

The mass transfer coefficients in the formula for the diffusion fluxes

$$J_{j,w} = \beta_j\,(c_{j,e} - c_{j,w}) \tag{3}$$

were taken identical and equal to $\beta_j = \beta_w = \alpha/c_p$.

Analysis of the Results of Computations

The investigated range of conditions in the incoming stream corresponded to regimes of large injections when the main contribution to the thermal balance on the surface is given by precisely the effect of material vapor injection. In this case the magnitude of the dimensionless rate of material gasification $\bar{G}_{\Sigma,w}$ is determined independently of the entrainment mechanism mainly by just the drop in stagnation enthalpy across the boundary layer and by the magnitude of the injection coefficient γ when using the approximate method. To prove this, dependences of the magnitude of the contribution due to the effect of injection of vapors of the material being fractured to the compressed layer in the heat balance on the surface

$$\eta_{\text{in}} = 1 - \frac{\alpha/c_p}{(\alpha/c_p)_0}$$

are presented in Fig. 1, as are also the magnitudes of the contribution of the chemical reactions on the surface of the body being fractured to the total heat balance

$$\eta_{\text{chem}} = q_{\text{chem}}/q_{\text{к},0}.$$

Results of computations of the dimensionless rate of material gasification $\bar{G}_{\Sigma,w}$ are presented in the figure. The data presented display the high accuracy of the computation $\bar{G}_{\Sigma,w}$ by using the HMT analogy (~20%).

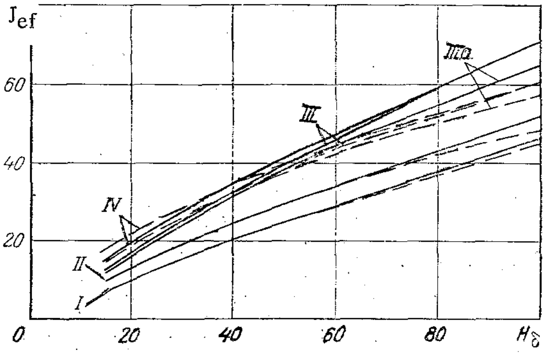

Fig. 4. Effective enthalpy of a glass-graphite material, J_{ef}, MJ/kg. See Figs. 1 and 2 for notation.

Here and henceforth, the error estimate is executed in that region where they reach their greatest values.

Let us note that even for $H_{\delta} > 40$ MJ/kg the quantities $\overline{G}_{\Sigma,w}$, computed for the different fracture schemes, do not differ by more than 15% despite the fact that the temperature T_w of the surface being heated differs by more than 600°K for the appropriate computations (Fig. 2). The quantity T_w in the regime of large injections is here determined uniquely from the condition of assuring the necessary material gasification rate. An increase in the degree of gasification of the products of destruction of the binder and the silicon dioxide is observed in the considered sequential complication of the material fracture mechanism on the one hand, and an intensification of the SiO_2 evaporation process [1] on the other. Consequently, a decrease in T_w corresponds to complication of the fracture mechanism, as is seen in Fig. 2.

It was noted in [1] that the most favorable conditions for the origination of ambiguity in the laws of glass-graphite body fracture occur when the parameter $p_e/(\alpha/c_p)_0$ increases. In order to illustrate this situation, results of computations performed for model III with a body bluntness radius of $R = 1$ m are superposed in Fig. 2. As is seen, the results of this investigation are in total agreement with the deductions of this paper. It was shown in [3] that the conditions for the occurrence of the mentioned ambiguity are improved during the progress of a heterogeneous chemical interaction between silicon dioxide and carbon in the solid phase. This circumstance is the reason for the origination of a nonmonotonic dependence $T_w(H_{\delta})$ within the framework of the scheme IV even for $R = 0.1$ m. Let us note that the error in calculating the quantity T_w for these models (when using the HMT analogy) does not exceed 1%.

One of the important parameters governing the mechanism of thermochemical fracture of a glass-graphite material is the silicon dioxide gasification factor $\Gamma_{SiO_2,\Sigma}$. The quantity $\Gamma_{SiO_2,\Sigma}$ is understood to be the total fraction of silicon dioxide being contained in the material that goes over into the gas phase. Results of a computation of the SiO_2 gasification factor are presented in Fig. 3. The unique increase of $\Gamma_{SiO_2,\Sigma}$ in the complication of the fracture mechanism is associated with the melt cooling noted above. For the differential carbon burnup scheme the value of this parameter is quite close to one and consequently, corresponding values are not superposed on this figure. The greatest error in the calculation of $\Gamma_{SiO_2,\Sigma}$ when using the approximate method of computing the HMT (18%) is observed within the framework of scheme I. It should also be noted that the error level remarked in the computation of $\Gamma_{SiO_2,\Sigma}$ is weakly responsive to a change in R, as the results of the investigations performed show.

The effective enthalpy of the material is understood to be the quantity of heat absorbed during entrainment of unit mass of material

$$J_{ef} = (q_{\kappa} - \sigma\varepsilon_w T_w^4)/G_{\Sigma,\infty}. \tag{4}$$

For materials of the class under consideration, the quantity J_{ef} is determined primarily by the value of the SiO_2 gasification factor, as becomes evident in a comparison of Figs. 3 and 4. Consequently, a growth of J_{ef} is observed with the complication of the fracture mechanism on the one hand, and the maximum error level of the parameter computation when using the HMT analogy is a quantity on the order of 20%, on the other.

The reason for the systematic exaggeration of the quantity J_{ef} obtained in solving the adjoint problem over the corresponding quantity obtained in computing the fracture by using the analogy between the HMT is that the convective heat flux attenuation function used in the approximate computations in the form (1) yields a reduced efficiency of flux attenuation for high vapor injection velocities. On the basis of the data presented, an analysis can be performed of the accuracy of computing the total material fracture rate (by using (4)) and the other characteristics that are of interest in analyzing the material fracture process.

Therefore, utilization of the approximate method of computing the HMT in a boundary layer permits evaluation of the parameters governing the process of thermochemical fracture, with sufficient accuracy for practice, in a broad range of conditions in the free stream, including conditions of developed gas flux ionization. The maximum errors in the calculation of all the characteristics listed did not exceed 20% for any version of the computation.

NOTATION

x, coordinate directed along the body surface, m; u, stream velocity projection on the x axis, m/sec; $\Gamma_{c,w}$, carbon gasification factor in the surface being heated; $\Gamma_{SiO_2,\Sigma}$, silicon dioxide gasification factor; T, temperature, °K; $G_{\Sigma,\infty}$, $G_{\Sigma,w}$, total material mass fracture and gasification rates, kg/m^2·sec; J_{ef}, effective material enthalpy, J/kg; φ_i, mass fraction of the i-th component in the initial material; q_k, convective heat flux, W/m^2; α/c_p, heat transfer factor, kg/m^2·sec; $\tau_{w,x}$, tangential component of the fraction stress tensor, kg/m^2·sec^2; J_i, c_i, mass diffusion flux (kg/m^2·sec) and the concentration of the i-th component; q_{chem}, heat flux due to progress of chemical reactions, W/m^2; H, stagnation enthalpy, J/kg; γ, injection factor; β_i, mass transfer coefficient of the i-th component, kg/m^2·sec; p, pressure, Pa; R, bluntness radius, m; ε_w, integrated degree surface emissivity; σ, Stefan–Boltzmann constant; Subscripts: w, heated surface of the material being fractured; 0, impermeable surface; e, boundary of the dynamic boundary layer; and δ, shock front.

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