considered in [10] of organizing near-wall turbulent flows by forming developed circulation zones at the surface of the streamlined body is promising. The results of computing the flow by a sub- and supersonic flow around a body with a forward separation zone, as displayed in Figs. 1 and 3, are an illustration of the positive properties of flows organized in such a manner.

NOTATION

x, y, coordinate along the stream and in a transverse direction; u, v, velocity components in the x and y directions, respectively; k, kinetic energy of the turbulent fluctuations; ε, rate of dissipation of k; ℓ, distance between the disc and the cylinder; r, disc radius; L, cylinder elongation; h, dimension of the difference mesh step; τ_w, friction on the wall; β, Falkner–Skan parameter; ψ, stream function; θ, an angular coordinate; M, Mach number; Re, Reynolds number; $Re_T = k^2/(\nu\varepsilon)$, turbulent Reynolds number; ν, kinematic viscosity coefficient; Tu, intensity of external flow turbulence, $(\ )'$, fluctuation; $(\bar{\ })$, time-average.

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THEORY AND EXPERIMENT IN THE PROBLEM OF THE INTERACTION OF HIGH-VELOCITY GAS FLOWS WITH MATERIALS

Yu. V. Polezhaev

UDC 533.6.011.6

An analysis is made of the intensive thermal action of a gas flow on a body in the flow. An examination is made of features of failure of such bodies and the difference between the melting and vaporization points of glass-plastics in a turbulent boundary layer compared to a laminar boundary layer.

The interaction of high-velocity gas flows with the surfaces of different bodies has been intensively studied for about 30 years. During this period, significant strides have been made in studying different processes and phenomena in the boundary layer of the bodies, on the body surface, and inside the heated layer of material. Experimental studies have been vigorously pursued and numerous types of test stands have been developed. Some of these stands have a maximum power of tens of thousands of kilowatts.

The present article focuses on analysis of the intensive thermomechanical action of a gas flow on a body in the flow, which is usually referred to as the problem of thermal protection. Such terminology is arbitrary to a considerable extent, since the body is acted upon and brought to failure not only by heat flows, but also by diffusion flows of the chemically active components and by mechanical loads in the form of pressure and friction gradients. In contrast to most of the studies published recently, here we analyze processes occurring on the surface undergoing failure with a supersonic flow and a turbulent boundary layer.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 53, No. 5, pp. 765-774, November, 1987. Original article submitted February 3, 1987.

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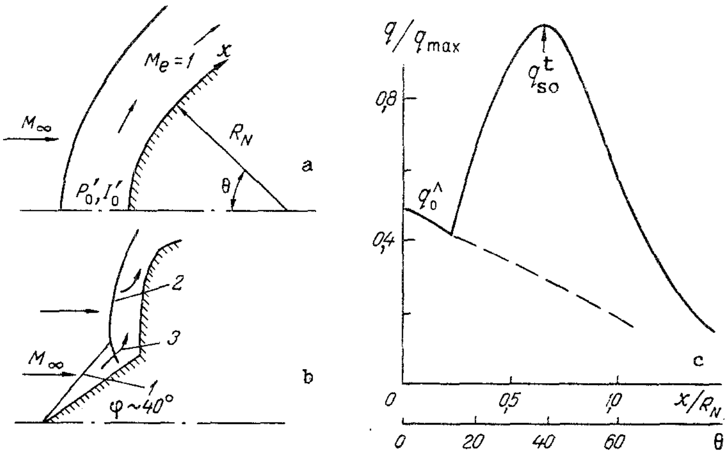


Fig. 1. Dynamics of change in the geometry of the body undergoing failure: a) initial shape (hemisphere); b) biconical shape with a central projection (1, 2, 3 — shock waves); c) distribution of heat flux over the generatrix of the hemisphere. θ, degrees.

In high-speed and high-temperature gas flows, heat transfer to the surface occurs through conduction and diffusion in the boundary layer adjacent to the surface. Protection involving the use of coatings which themselves disintegrate is a highly efficient means of blocking the convective heat flow. This form of protection is also of interest from a scientific viewpoint in connection with the fact that the gasdynamic and heat- and mass-transfer processes are coupled in this case, i.e., the occurrence of the latter not only depends on the former but also actively influences it.

As an example, we will examine the seemingly paradoxical case of the formation of a depression on the front surface of a body washed by a dense, supersonic gas flow. It is known that under steady-state flow conditions, over time the body can assume one of two stable geometric forms: ellipsoidal in the case of a laminar boundary-layer flow; conical with a turbulent boundary layer. The latter is seen mainly in the case of meteorites, but theoretical studies show that this form is possible only at very high Reynolds numbers — when the zone of transition from laminar to turbulent flow in the boundary layer is directly adjacent to the neighborhood of the forward critical point of the body.

The shape of the front surface is far from meteoritic in the overwhelming majority of experimental studies conducted on models subjected to failure in high-temperature gas flows. The reason for this is connected with the limited range of Reynolds number which can be reproduced in tests. The threshold Reynolds number at which the shape of the surface can change from that associated with laminar blunting to that associated with meteorites depends on many factors, one of the most important being the roughness of the surface. In contrast to the classical sandy roughness on models used in tests, the roughness of the surface connected with the transition is serrated, not unlike a cockle shell.

As tests have shown, stable results are obtained when the models failing in the flow are made of polymethylmethacrylate ("organic glass"). The serrated roughness on the surface of such models significantly lowers the critical Reynolds number associated with the transition from laminar to turbulent flow in the boundary layer. Figure 1a and b shows the dynamics of the time change in the form of the model from the initial spherical shape to the steady-state biconical shape. Meanwhile, the angle of the second cone in the middle part of the front surface differs by a factor of nearly two from the angle of the first cone. This is evidence of the formation of several conical projections on the nearly flat (quasiplanar) end.

It seems at first glance that flow about such a body is impossible without separation of the flow at the contact point of the two cones or the point where the conical projection contacts the end. However, heat transfer generally decreases sharply in separation regions compared to regions in which the flow is still attached to the surface. Thus, it is impossible for a steady-state form of the failed surface to exist under such conditions. Moreover, over time the shape of the body approaches that for which the projection of the linear failure rate on the axis of the body is balanced at all points and nears the maximum value possible under the given conditions. In particular, with two heat-flux maximums on the front surface of the body (Fig. 1c), the failure rate is made to conform to the higher level due to the change in the geometry of the body.

In the neighborhood of the forward critical point for a laminar regime, heat transfer occurs at a rate proportional to the square root of the Reynolds number. It is not hard to show that in supersonic flow about a spherical body of radius R_N, the heat flux to the critical point is proportional to the below quantity [1]:

$$q_0^{\ell} \sim \sqrt{P_0'/R_N}\,(I_0' - I_w).$$

Here, P_0' and I_0' are the pressure and enthalpy of the retarded flow; I_w is the enthalpy of the gas on the body surface undergoing failure.

The heat-flux distribution along the body surface depends on the pressure distribution P(x) and the flow regime in the boundary layer. Given a sufficiently high-velocity incoming flow, so-called "hypersonic stabilization" begins. This phenomenon [2] is based on the fact that the pressure distribution along the body surface P(x) depends mainly only on the shape of the surface (and is nearly independent of the Mach number). Thus, it is possible to substantially simplify our analysis, since, regardless of the shape of the body, the turbulent heat-transfer maximum occurs at the sonic point on the surface (more precisely, in the neighborhood of the line corresponding to the passage of the speed of sound by the retarded gas flow behind the shock wave).

The pressure of the gas at the sonic point is directly proportional to the pressure of the retarded flow

$$P(x_{so})/P_0' = \left[\frac{k+1}{2}\right]^{\frac{k}{k-1}},$$

where k is the adiabatic exponent. This makes it possible to describe the maximum heat flux in the turbulent boundary layer with the same set of parameters as was used for laminar flow [3]:

$$q_{so}^{t} \sim (P_0')^{0,8} R_N^{-0,2}\,(I_0' - I_w).$$

The ratio of the two local heat-flux maxima

$$q_{so}^{t}/q_0^{\ell} \sim \sqrt[3]{P_0' R_N}$$

will be greater, the more rapid the increase in the product $P_0'R_N$. During the disintegration of the surface, as noted above, the projection of the rate of failure and, thus, the heat fluxes at different points should be equal. An increase in stagnation pressure P_0' should be accompanied by a reduction in the blunting radius R_N at the critical point, i.e., the model becomes sharper and approaches meteoritic form [4].

The appearance of a depression on the profile of the body changes the gasdynamic flow pattern. A single shock wave is replaced by a system of shocks (Fig. 1b). The first shock arises from the central projection of the body, the second develops from the quasiplanar end, and the third originates in the region of intersection of the first two. Under certain conditions, the pressure of the retarded flow may be higher after it has been subjected to a system of oblique and normal shocks than after a single normal shock. In other words, the appearance of a system of shock waves intensifies heat transfer in the depression and enlarges it. Here, it is important to note that the half-angle of the conical projection is about 40° and corresponds to the range of cones for which supersonic flow remains attached in a turbulent boundary layer even in the presence of a shock wave from the end [5].

Our example pertains to the case of "strong interaction" of an incoming flow with a body undergoing disintegration in the flow, when the body is not simply acted upon thermally and mechanically by the flow but itself significantly restructures the flow field. Of fundamental importance here is the turbulent regime of flow in the boundary layer.

Our second example also pertains to the problem of turbulence, although in this case the distribution of the gasdynamic parameters will be considered invariant. Two competing processes take place on the surface of glass-plastics placed in a high-speed gas flow: melting and vaporization. The lower the heat flux and the greater the mechanical load, the greater the quantity of material carried off in molten form. Conversely, the more intensive the

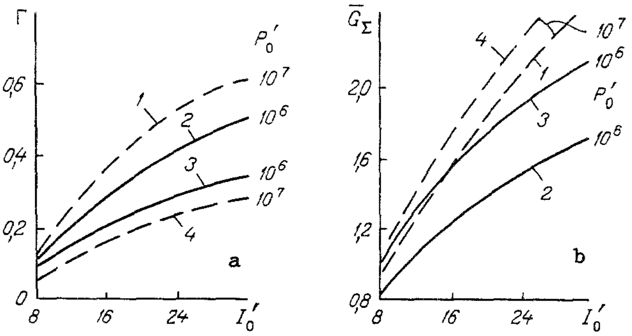


Fig. 2. Dependence of the degree of gasification (a) and dimensionless rate of disintegration (b) on flow stagnation enthalpy with turbulent (1, 2) and laminar (3, 4) regimes in the boundary layer. Stagnation pressure equal to 10^7 (1, 4) and 10^6 Pa (2, 3). I_0', MJ/kg.

heat-and-mass transfer and the lower the shear stresses, the greater the degree of gasification of the material Γ. The degree of gasification is equal to the ratio of the amounts of material carried off in gaseous and molten form: $\Gamma = G_w/G_m$. As was shown in the first example, the level or scale of the thermomechanical loading is fully characterized by the stagnation pressure P_0' and stagnation enthalpy I_0' of the gas flow. The pressure distribution over the surface of a blunted hemispherical body of radius R_N can be described in a Newtonian approximation by the equation

$$P_e = P(x) = P_0' \cos^2(x/R_N).$$

A change from laminar to turbulent flow is not accompanied by a change in the dependence of the pressure gradient on the stagnation pressure P_0' and the size of the body R_N because, in accordance with the Reynolds analogy, the friction depends on the heat-transfer coefficient $(\alpha/c_p)_w$:

$$\frac{d\tau_w}{dx} = 1{,}7\,(\alpha/c_p)_w \left(\frac{du_e}{dx}\right)_0.$$

Here, $(du_e/dx)_0$ is the velocity gradient on the external boundary of the boundary layer. Near the critical point, it depends only on the dimensions of the body and the stagnation enthalpy I_0'. The heat-transfer coefficient

$$(\alpha/c_p)_w = q_w/(I_0'/I_w)$$

in a laminar boundary layer is

$$(\alpha/c_p)_w^{\ell} \sim \sqrt{P_0'/R_N},$$

while the dependence on pressure in a turbulent boundary layer is more pronounced:

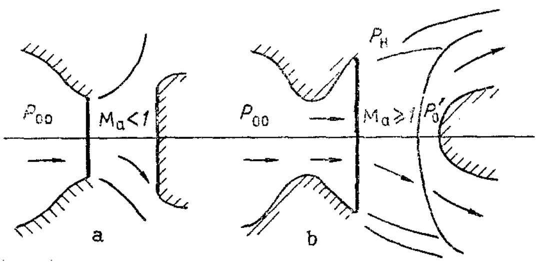
$$(\alpha/c_p)_w^{t} \sim (P_0')^{0,8} R_N^{-0,2}.$$

Despite the constancy of the body's geometry and the known pressure distribution along the generatrix of the body, a rigorous solution of the problem of thermomechanical failure is possible only in a conjugate formulation. Due to the complexity of this problem, systematic solutions have been obtained only for a laminar boundary layer in the neighborhood of the critical point [1, 6]. These calculations have shown that the analogy between heat and mass transfer [1] is satisfied with acceptable accuracy within a broad range of enthalpies I_0' — including the region of developed ionization of the components of the incoming flow and with allowance for the many dozens of components of the disintegration products. The calculation also showed that the effect of injection can be considered in the form of a correction factor Ψ_q in the expression for heat flux:

$$\Psi_q = q_w(\Gamma > 0)/q(\Gamma = 0) = \frac{(\alpha/c_p)_w}{(\alpha/c_p)_0} = \frac{1}{3(\gamma\bar{G}_w)^2 + \gamma\bar{G}_w + 1}.$$

Here, $\bar{G}_w$ is the dimensionless rate of entrainment, $\bar{G}_w = \bar{G}_w/(\alpha/c_p)_0$, while γ is a multiplier dependent only on the molecular weights of the mixtures of gases present in the incoming flow and injected from the surface undergoing disintegration: M_e and M_v.

With allowance for the heat and mass transfer analogy and the effect of injection, the rate of vaporization of the molten glass film is described by the equation [1]:



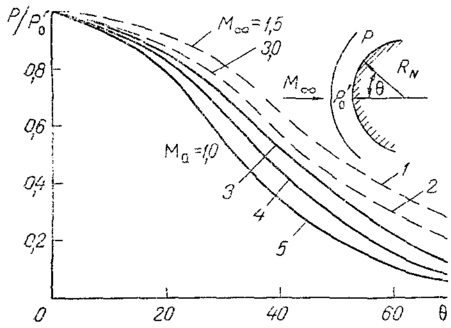


Fig. 3 Fig. 4

Fig. 3. Testing schemes in subsonic (a) and supersonic (b) high-temperature jets.

Fig. 4. Pressure distribution along the generatrix of a hemispherical model in uniform (1, 2) and divergent (3-5) flows. The ratio of the model size to the nozzle-edge diameter is 0.6 (curve 3), 0.8 (4), and 1.0 (5).

$$G_w = (\alpha/c_p)_w P_v M_v/[P_e M_\Sigma - P_v M_v],$$

where the product of the partial pressure of the vapors P_V and their molecular weight M_V can be regarded as a known function of the temperature of the surface T_W.

In the sublimation regime (when the gasification coefficient $\Gamma = 1$), the dimensionless vaporization rate $\overline{G}_W = G_W/(\alpha/C_p)_0$ is independent of the stagnation pressure P_0'. Instead, it is completely determined from the energy balance on the disintegrating surface as a function of stagnation enthalpy I_0' [1]. Conversely, the temperature of the surface T_W depends mainly on the stagnation pressure P_0'. This is easily established by means of the equation written above. In the limit $G_W \to \infty$, we obtain

$$P_v M_v = P_v(T_w) M_v(T_w) = P_e M_\Sigma.$$

In the general case, along with the vaporization rate G_W, ablation of the glass-plastic also depends on the mass flow of material in the molten film. Near the critical point, this flow can be described through a simple analytical expression:

$$G_m = \frac{2\rho\delta^2}{\mu(T_w)}\left[\frac{d\tau_w}{dx} - 2\delta\frac{d^2P_e}{dx^2}\right].$$

Together with the shearing forces – the gradients of friction ($d\tau_W/dx$) and pressure (d^2P_e/dx^2) – this relation takes into account the viscosity of the molten glass $\mu(T_W)$, the density of the latter, and the thickness of the film δ:

$$\delta = \lambda/[ncG_\Sigma] \sim 1/[n\overline{G}_\Sigma(\alpha/c_p)_0].$$

Here, $n = \beta/T_W$ is a parameter accounting for the dependence of the viscosity of the melt on temperature, $\mu \sim \exp(\beta/T)$.

Inserting the expressions for the friction and pressure gradients, we obtain:

$$G_m/G_w \sim \frac{P_0'}{(\alpha/c_p)_0^2}(P_v M_v \mu n^2)\left[a + b\frac{P_0'}{(\alpha/c_p)_0^2}\right],$$

where a and b are certain parameters dependent on the size of the body R_N and the stagnation enthalpy I_0'.

As calculations show, the product in the parentheses ($P_V M_V \mu n^2$) can be assumed constant to within ±30% over the entire possible range of surface temperatures T_W.

All of these simple considerations help clarify the main laws governing the ablation of glass-plastics with laminar and turbulent boundary-layer flow. It was believed earlier that the difference between these two flow regimes amounted only to a reduction in the coefficient γ in regard to the effectiveness of blocking heat flow with injection of vaporization products G_W. However, refined numerical calculations (Fig. 2) revealed y et one other noteworthy fact: the effect of the pressure P_0' on the fraction of vaporization $\Gamma = G_W/G_\Sigma$ and the dimensionless failure rate $\overline{G}_\Sigma = G_\Sigma/(\alpha/C_p)_0$ differs qualitatively as well as quantitatively for laminar and turbulent boundary layers.

Since $\Gamma = G_w/G_\Sigma = 1/[1 + (G_m/G_w)]$, and $\bar{G}_\Sigma = \bar{G}_w + \bar{G}_m = \bar{G}_w[1 + (G_m/G_w)]$, they both reduce to the previously derived relation in which the ratio $P_0'/(\alpha/C_p)_0^2$ is present as a parameter.

With a laminar flow regime in the boundary layer, the heat-transfer coefficient is proportional to the square root of pressure. Thus, the degree of gasification and the dimensionless rate of failure of the glass-plastic are nearly independent of the pressure P_0'. The determining parameter in this case is the stagnation enthalpy of the flow I_0'.

With a turbulent regime of flow in the boundary layer, the parameter $P_0'/(\alpha C_p)_0^2$ is no longer constant. Thus, an increase in stagnation pressure ahead of the model will be accompanied by a reduction in ablation in the molten film in accordance with the relation

$$G_m/G_w \sim (P_0')^{-0.6}\,[a + b\,(P_0')^{-0.6}].$$

The gasification coefficient Γ proves to be 2-3 times greater in the turbulent case than in a laminar boundary layer. Meanwhile, it increases with an increase in pressure (complete opposition to laminar flow). The effectiveness of using ablating glass-plastics increases with an increase in the intensity of turbulent heat transfer (Fig. 2).

Experimentation plays a large role in the study of the interaction of high-speed gas flows with disintegrating materials. It offers a representation of the essence of the physical processes taking place, and in many cases an experiment is the only source of the quantitative information necessary to close theoretical models.

However, power limitations make it impossible for laboratory experiments to cover the entire range of the governing parameters and necessitate a relatively narrow specialization of the testing equipment used. Each testing unit is used to reproduce just one given factor. As a result, there is a worldwide tendency for the number of units to continually increase. The number of wind tunnels has increased twentyfold since World War II, and a significant percentage of these tunnels are equipped with heaters for the working medium.

The large number of experimental units makes acute the problem of comparing the results obtained on this equipment and generalizing the data in the form of criterional relations which are valid outside the range of the parameters of the respective experiments. In contrast to hydrodynamics, classical gasdynamics, or the theory of heat conduction, the interaction of high-velocity gas flows with disintegrating materials is a basically nonlinear process. This precludes the construct of a system of exact scaling criteria.

Given these conditions, theoretical models or mechanisms become more important. This includes consideration of the elementary physico-chemical transformations of individual components of the materials while they are being heated and are in contact with chemically active components of the incoming gas flow. Thus, mechanisms of interaction have been developed in thermal protection theory for sublimating, melting (glassy), and chemically active (graphitic) ablating materials.

Comparison of theoretical data with experimental results shows that quantitative as well as qualitative agreement can be obtained in many cases. This in turn makes it possible to purposefully plan testing methods and facilities. We will illustrate this by using several examples.

The results of calculations of the process of disintegration of glass-plastics shown in Fig. 2 indicate that stagnation enthalpy I_0' is of decisive importance in a laminar flow regime and that the stagnation pressure P_0' has a much weaker effect. The effect of the size of the body R_N is equally weak.

These findings were the basis for a widely used approach whereby only stagnation enthalpy is reproduced on the test stand, although flow velocity (or Mach number), model size, and the pressure ahead of the model (or the Reynolds number) can be varied within broad ranges determined by considerations of convenience or available power. In particular, a large amount of experimental information is obtained from subsonic high-temperature units (Fig. 3a), which make it possible to test relatively large models while using a minimum of power. However, the small pressure drop in the flow and, thus, the low rate of heat transfer create certain procedural problems stemming from the long time required to establish a constant ablation rate. Errors made in allowing for the transient period lead to large errors in the measurement of the dimensionless ablation rate and other characteristics of the process.

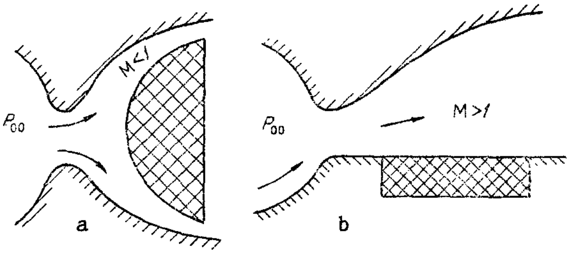


Fig. 5. Testing schemes in a subsonic shell (a) and a supersonic model channel (b).

The method of testing in the supersonic jet of a high-temperature unit (Fig. 3b) makes it possible to significantly increase the heat flux to the model surface. However, theoretical studies are necessary in this case to select the optimum testing procedures. The main problem is that with a limitation on the gas pressure in the precombustion chamber of the unit P_{00}, it is undesirable to accelerate the flow in the nozzle to Mach numbers M_a greater than two or three because the pressure loss in the main shock ahead of the model will be greater, the higher the value of M:

$$P_0'/P_{00}' \sim \left[\frac{k+1}{2kM^2-(k-1)}\right]^{\frac{1}{k-1}}\left[\frac{(k+1)M^2}{2+(k-1)M^2}\right]^{\frac{k}{k-1}}.$$

As a result, the heat flux, proportional to P_0', decreases in value, and all of the advantages of a high-head supersonic jet may be lost.

At the same time, the limitation on the Mach number M_a at the nozzle edge with a high ratio of P_{00} to the ambient pressure P_H creates a flow characterized by a high degree of divergence (an underexpanded jet), and all of the parameters in such a flow are distributed quite differently from a uniform infinite flow. Figure 4 shows the pressure distribution on the surface of a sphere in a sonic jet ($M_a = 1$). The dashed lines show the pressure distribution in a uniform flow with different Mach numbers M [7]. Curves 3-5 in Fig. 4 show the change in the pressure distribution on spheres of successively greater diameters: from 0.6 and 0.8 to 1.0 of the diameter of the nozzle edge. By enlarging the model, we increase the effect of divergence and can therefore simulate an increase in the Mach number in a uniform flow. However, it is still not possible to extend this principle to other model shapes without a preliminary numerical analysis [3, 7].

Investigators have to find new schemes for organizing the flow in their attempt to obtain high Reynolds numbers and a turbulent flow regime in the boundary layer on ablating models. Figure 5 shows two such schemes. The first (a) employs a subsonic shell in which flow is subsonic everywhere except for the edge of the model, where sonic velocity is reached. The second scheme (b) is called a model channel, since the distribution of pressure along the surface of the model and the local Reynolds numbers are chosen so that they correspond to the actual distribution on the test body behind the main shock wave. The selections are made by means of a special profiling of the nozzle wall.

The second of the above two variants requires solution of the inverse problem: given the law of change in heat flux on the model, establish the distribution of the gasdynamic parameters and use this distribution to design a special testing unit. This example most completely characterizes the combination of theory and experiment which is typical of current investigations of the interaction of high-speed gas flows with ablating materials.

NOTATION

x, longitudinal coordinate; R_N, characteristic dimension of the body; P, pressure; T, temperature; I, enthalpy; q, heat flux; k, adiabatic exponent; G, ablation; Γ, degree of gasification; α/c_p, heat-transfer coefficient; u_e, velocity on the external boundary of the boundary layer; M, Mach number; Ψ_q, ratio of the heat fluxes during injection; M_e, M_Σ, M_v, molecular weights of the gas mixture in the external flow, on the ablating surface, and in the injection products; λ, ρ, c, μ, δ, thermal conductivity, density, heat capacity, viscosity, and thickness of the molten film. Indices: w, surface of the body; e, flow around the body; m, melt; v, vapor; 0, parameters of the retarded flow; so, sonic point; 00, total pressure in the precombustion chamber of the tunnel; a, on the nozzle edge in the open working part of the nozzle.

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MATHEMATICAL MODEL OF THE PROCESS OF THERMAL DESTRUCTION OF POLYMER MATERIALS UNDER INTENSE THERMAL EFFECTS

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UDC 66.092:536.42

It is proposed to describe heat- and mass-transfer processes in decomposing materials by taking into account both the chemical and physical transformations and the phase transition temperatures.

The one-dimensional process of heat and mass transfer in polymer-based materials with thermal decomposition taken into account is described by the differential equation

$$c\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) - c_g G_g \frac{\partial T}{\partial x} \pm \sum_i Q_i \frac{dC_i}{dt} \pm \sum_i Q_{\mathrm{p}i} \frac{dx_i}{dt}, \tag{1}$$

where dC_i/dt, dx_i/dt are the chemical reaction and physical transformation rates with the thermal effects Q_i and Q_{pi}.

Taken into account in (1) are physical processes such as evaporation, boiling, desorption of the initial products and decomposition products, etc. The transformation rates are associated in individual stages with the rate constants k_i and k_{pi}:

$$dC_i/dt = -k_i C_i^{\overline{n}},\ dx_i/dt = -k_{\mathrm{p}i} x_i. \tag{2}$$

We obtain as a result of integrating (2) for nonisothermal heating conditions and a reaction order $\overline{n} = 1$

$$C_i = C_{0i} \exp\left(-\int_0^t k_i dt\right),\quad x_i = x_{0i} \exp\left(-\int_0^t k_{\mathrm{p}\,i} dt\right).$$

Substituting values of the variables C_i and x_i into (2) and then into the initial equation (1), we obtain

$$c\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) - c_g G_g \frac{\partial T}{\partial x} \pm \sum_i Q_i k_i \exp\left(-\int_0^t k_i dt\right) \pm \sum_i Q_{\mathrm{p}\,i} k_{\mathrm{p}i} \exp\left(-\int_0^t k_{\Phi i} dt\right). \tag{3}$$

Analysis of (2) and (3) permits making the following deduction. Under moderate thermal effects the temperature of a decomposing material is not high and is close to the equilibrium temperature of the beginning of decomposition $T_\infty = \Delta H/\Delta S$, where ΔH, ΔS are the changes in enthalpy and entropy of the chemical transformation, depolymerization, say [1].

D. I. Mendeleev Moscow Chemicotechnological Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 53, No. 5, pp. 774-781, November, 1987. Original article submitted January 30, 1987.