RATE OF MATERIAL DESTRUCTION UNDER UNILATERAL HEATING

G. A. Frolov, Yu. V. Polezhaev,
and V. V. Pasichnyi

UDC 536.2.083

A linear dependence is established between the quasistationary rate of mass entrainment and the square root of the enthalpy of the stagnation flow. An equation is proposed for its computation in a broad range of external action parameters.

One of the fundamental parameters characterizing the efficiency of materials under unilateral heating is the rate of mass entrainment from the surface in a quasistationary destruction mode. It is determined by external conditions (heat flux, pressure and deceleration enthalpy) and the nature of the material. Starting from the governing mechanism of the destruction, a whole manifold of heat shielding materials can be divided into several classes [1]. As a rule, its own computational method is developed for each class. However, they can be used only for known thermophysical and kinetic parameters whose determination is a sufficiently complex independent problem. Since these parameters are mainly unknown for new materials, their efficiency is often estimated from the results of experimental investigations represented in the form of a linear dependence of the effective enthalpy on the stagnation enthalpy of the impinging gas flow [1]:

$$I_{\text{ef}} = a + bI_e. \tag{1}$$

A comparison with exact computational formulas exhibits the limitation of such an approach. No physical foundation is given here to the constants a and b, which makes their selection difficult for new materials.

An attempt is made in this paper to obtain as simple an engineering formula as (1), on the one hand, and to find a physical interpretation of the coefficients a and b, on the other.

The mass entrainment rate of vitreous materials is computed by means of a formula obtained from the heat-balance equation [1]. For $\gamma\bar{G}_w < 0.4$ it has the form

$$G_\Sigma = \frac{(\alpha/c_p)_0 (I_e - I_w) - \varepsilon\sigma T_w^4}{\Gamma[\Delta Q_w + \gamma(I_e - I_w)] + \bar{c}_p(T_w - T_0)}, \tag{2}$$

while for $0.4 < \gamma\bar{G}_w < 1.2$ it can be written as

$$G_\Sigma = \frac{(\alpha/c_p)_0 [1{,}012 - 1{,}16(\gamma\bar{G}_w) + 0{,}325(\gamma\bar{G}_w)^2](I_e - I_w) - \varepsilon\sigma T_w^4}{\Gamma\Delta Q_w + \bar{c}_p(T_w - T_0)}. \tag{3}$$

Dependences (2) and (3) are indeed used to compute the rate of destruction of thermoplastic materials. In this case the radiation energy ($T_w \leq 1000$°K) can be neglected and the coefficient of evaporation Γ can be equal to one.

Results of numerical computations of the process of graphite sublimation are represented in [2] in the form of a simple approximation for the concentration of carbon

$$\tilde{c}_{c,w} = 0{,}15 - 2{,}4\cdot 10^6 P_e^{-0{,}67} \exp[-61400/T_w]. \tag{4}$$

The rate of carbon destruction in the sublimation mode is related to the rate of diffusion combustion

$$G_w^{(s)} = 6{,}67\, G_w^{(D)} \tilde{c}_{c,w}, \tag{5}$$

where

$$G_w^{(D)} = 0{,}13(\alpha/c_p)_0, \tag{6}$$

Institute of Material Science Problems, Academy of Sciences of the Ukrainian SSR, Kiev.
Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 52, No. 4, pp. 533-540, April, 1987. Original article submitted February 25, 1986.

0022-0841/87/5204-0379$12.50

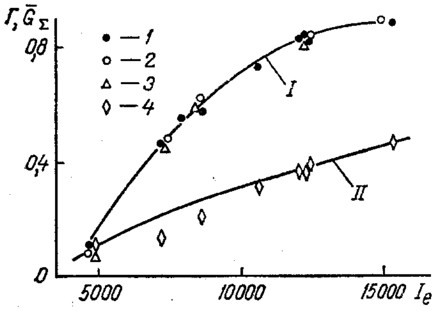

Fig. 1

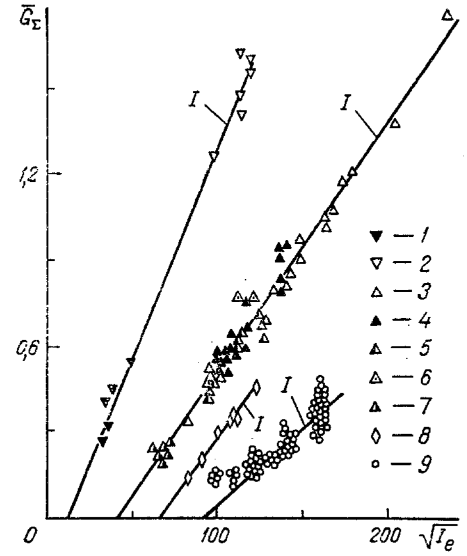

Fig. 2

Fig. 1. Dependence of the gasification coefficient Γ and the dimensionless entrainment rate $\bar{G}_\Sigma$ on the stagnation enthalpy for materials based on quartz glass: 1-4) experiment; 1-3) gasification coefficient: 4) dimensionless entrainment rate; I) processing by least squares; II) computation using (2); 1, 4) doped glass-ceramic (0.5% Cr_2O_3); 2) pure glass-ceramic; 3) quartz glass. I_e, kJ/kg.

Fig. 2. Dependence of the dimensionless entrainment rate $\bar{G}_\Sigma$ on the square root of the stagnation enthalpy: 1, 2) polytetrafluorethylene [6]; 3-7) glass-plastic based on silicic fiber and epoxy binder; 8) doped quartz glass ceramic (0.5% Cr_2O_3); 9) graphite [9]; 3) data in [8]; 1-5, 8) $P_e \approx 1 \cdot 10^5$ Pa; 6) $P_e = 0.3 \cdot 10^5$ Pa; 9) $P_e = (0.3\text{-}4.2) \cdot 10^5$ Pa; 1) argon; 2, 5) nitrogen; 3, 4, 6, 8, 9) air; 7) products of kerosene–oxygen propellant combustion, $P_e = 3.5 \cdot 10^5$Pa; I) least squares processing. $\sqrt{I_e}$, $(kJ/kg)^{0.5}$.

and $(\alpha/c_p)_0$ can, according to [1], be taken approximately equal to

$$(\alpha/c_p)_0 \approx 0{,}132 \sqrt{\frac{P_e}{R}}. \tag{7}$$

Here P_e, $Pa \cdot 10^{-5}$; R, m; and T_w, °K.

For a known surface temperature, the gasification coefficient G_Σ and the total thermal effect of the physicochemical transformations on the surface Γ that characterize the degree of realization of the "thermodynamic possibilities" of the material under given external flow parameters must be known to compute ΔQ_w by means of (2).

In certain cases the gasification coefficient can be determined experimentally for vitreous materials. It is shown in [3] that it depends mainly on the stagnation enthalpy of the impinging gas flow. It is seen from Fig. 1 that the gasification coefficients of quartz glass, pure and doped quartz glass-ceramics are practically in agreement although the degree of transparency of these materials differs significantly and the rate of entrainment of quartz glass specimens is twice that for doped glass-ceramics under identical heating conditions [4].

Processes on the surface of quartz glass were considered in [1] and the thermal effect of the total physicochemical transformations was computed in a broad range of external flow parameters. These computations permit two deductions to be made. Firstly, ΔQ_w varies comparatively little and a certain mean value of 11,000 kJ/kg can be used in all cases, and secondly, its value equals ~12,000 kJ/kg for a boiling temperature in the $10^3\text{-}10^6$ Pa pressure range.

The fundamental criteria for the comparison of heat shield materials are the effective enthalpy and the dimensionless rate of mass entrainment, which is determined by the formula

$$\bar{G}_\Sigma = G_\Sigma/(\alpha/c_p)_0. \tag{8}$$

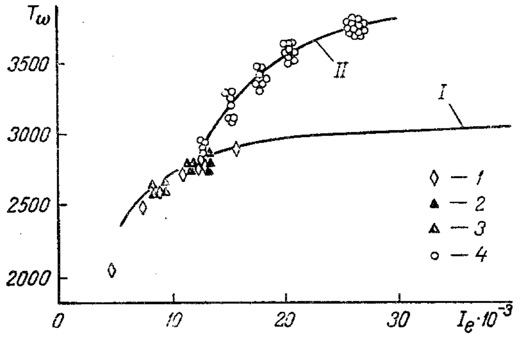

Fig. 3

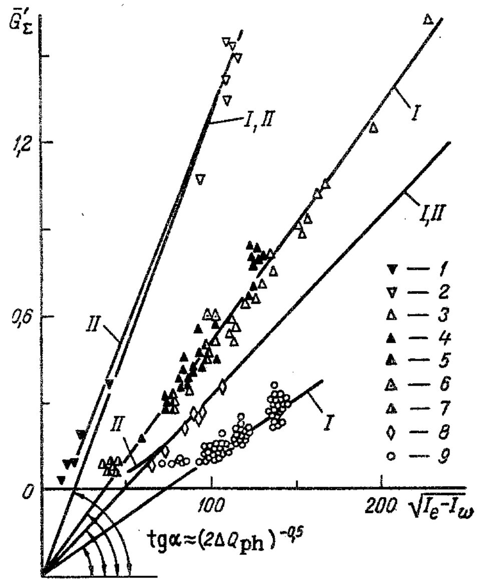

Fig. 4

Fig. 3. Dependence of the surface temperature on the stagnation enthalpy: 1) doped quartz glass-ceramic [3, 4]; 2, 3) glass-plastic based on silicic fiber and epoxy binder; 2) air; 3) nitrogen [7]; 4) graphite, $P_e \approx 1 \cdot 10^5$ Pa, $(\alpha/c_p)_0 = 1$ kJ/m^2·sec ±30% [9]; 1-4) experiment; I) computation [1] for $R = 7 \cdot 10^{-3}$ m and $\varepsilon = 0.9$; II) least squares processing. T_w, °K and I_e, kJ/kg.

Fig. 4. Dependence of the dimensionless entrainment rate G'_Σ on $\sqrt{I_e - I_w}$: notation for the experimental points 1-9 the same as in Fig. 2; I) computation using (10); II) computation using (2), (3). $\sqrt{I_e - I_w}$, (kJ/kg)$^{0.5}$.

The dimensionless rate of mass entrainment is often considered as a function of the stagnation enthalpy of the gas flow. In computing $\bar{G}_\Sigma$ by means of (2) (Fig. 1, curve II), experimental values of the free gas stream parameters and the gasification coefficients were used. The mean integral specific heat was taken at 1.3 kJ/(kg·K) [5]. The specimen density was ~2000 kg/m^3. Values of the rate of destruction (points 4) were found by least squares from the results of testing specimens for different times under the conditions of one heating mode. The error in determining the entrainment rate, computed for a 0.95 fiducial probability, does not exceed 15%.

Since the entrainment rate depends on many parameters according to (2), then as should be expected, $\bar{G}_\Sigma = f(I_e)$ has a sufficiently complex nature. However, if $\bar{G}_\Sigma$ is considered as a function of the square root of the stagnation enthalpy, then this dependence can be represented in a first approximation by the equation

$$\bar{G}_\Sigma = a\sqrt{I_e} - b, \tag{9}$$

i.e., is a straight line. Here a and b are constants for the given material. It turns out that the dependence (9) is characteristic not only for a quartz glass-ceramic but also for materials of other classes (Fig. 2).

The data for the epoxy binder glass-plastic, shown in Fig. 2 (points 3-7), are obtained in this paper and in [7, 8]. Tests of this material are conducted in the range of heat fluxes 2100-22,700 kW/m^2, stagnation enthalpy of 4700-56,000 kJ/kg, and stagnation pressures $(0.3\text{-}3.5) \cdot 10^5$ Pa in nitrogen, air, and kerosene–oxygen propellant combustion product flows. The results of tests on graphite (point 9) are taken from [9]. For these tests the stagnation pressure was within the limits $(0.3\text{-}4.3) \cdot 10^5$ Pa, the heat fluxes varied ten times, and the stagnation enthalpy 2.5-3 times. The authors of [9] note that the difference between the experimental and theoretical values of the mass entrainment rate is due, at least partially, to the entrainment in the form of particles. Since this discrepancy is most strongly manifest at temperatures above 3700°K, then only the test results obtained at surface temperatures up to 3750°K are shown in Fig. 2.

The surface temperature of the material under consideration is presented in Fig. 3. It was determined on specimens with $R_{ef} = 10.5 \cdot 10^{-3}$ m for the doped quartz glass-ceramic.

TABLE 1. Results of Processing the Experimental Dependences $\bar{G}_{\Sigma} = f(\sqrt{I_e})$ and $\bar{G}'_{\Sigma} = f(\sqrt{I_e - I_w})$ by Least Squares

Material	T_{ph}, °K (source)	$2\Delta Q_{ph}$, kJ/kg [1]	6.79 H (T_{ph}), kJ/kg [11]	$\bar{G}_{\Sigma}=a\sqrt{I_e}-b$			$\bar{G}'_{\Sigma}=\frac{1}{\sqrt{H}}\sqrt{I_e-I_w}-b$		
				$a\cdot 10^3$	b	$\sigma'\cdot 10^2$	H, kJ/kg	b	$\sigma'\cdot 10^2$
Polytetrafluorethylene	1000 [1]	3800	—	14,7	0,175	6,5	4400	0,22	6,7
Glass-plastic based on silicic filler and epoxy binder	3050 [1]	14800	—	8,64	0,35	5,6	15240	0,3	4,9
Doped quartz glass-ceramic (0.5% Cr_2O_3)	3050 [1]	24000	25370	8,19	0,55	0,9	25350	0,32	0,4
Graphite	4130 [11]	56000	58100	5,4	0,51	4,5	58680	0,3	3,4

Brightness temperature measurements were performed in the visible spectrum band ($\lambda = 0.65 \cdot 10^{-6}$ m) by a photoelectric pyrometer. Emissivity values are taken from [10]. The weak dependence of the surface temperature on the body size is noted in [1]. Starting with $I_e \geq$ 10,000 kJ/kg, it is practically independent of the quantity $(\alpha/c_p)_0$ and determined completely by the stagnation pressure. The experimental values of the temperature (point 1) are in good agreement with the computation [1] for $R = 7 \cdot 10^{-3}$ m and $\varepsilon = 0.9$. Since the surface temperature of a glass-plastic using a silicic filler and epoxy binder agrees with the computation for quartz glass (points 2, 3) for $I_e < 15{,}000$ kJ/kg, then the computed values obtained for quartz glass can apparently be considered for higher values of the stagnation enthalpy. The value of the surface temperature of polytetrafluorethylene can be taken equal to 1000°K [1].

The experimental results for a known surface temperature (see Fig. 2) can be represented in the form $\bar{G}'_{\Sigma} = f(\sqrt{I_e - I_w})$ (Fig. 4). Here $\bar{G}'_{\Sigma} = \bar{G}_{\Sigma}\,(I_e - I_w)/(I_e - I_{c.w})$, i.e., the dimensionless entrainment rate is considered as though with respect to the initial drop in the enthalpy or the heat flux on a cold surface. Such processing of the results permits reduction of the linear dependence $\bar{G}_{\Sigma} = f(\sqrt{I_e})$ to one "focus," approximately equal to 0.3, and the proposal of an equation of the form

$$\bar{G}'_{\Sigma} = \frac{1}{\sqrt{H}}\sqrt{I_e - I_w} - 0{,}3 \tag{10}$$

for the computation of $\bar{G}'_{\Sigma}$ in the absence of combustion on the surface.

The parameter H in this formula has the dimensionality kJ/kg and its magnitude is approximately twice the value of ΔQ_{ph}. In this case the ΔQ_{ph} for polytetrafluorethylene is understood to be the heat of decomposition, for the glass-plastic and quartz glass-ceramic the total thermal effect of the physicochemical transformations at the boiling temperature, and for graphite the maximal value of the heat of sublimation.

It is shown in [7] that for the majority of simple substances and silicon dioxide, the thermal evaporation effect can be determined from the formula

$$\Delta Q_e \approx 3{,}4\,H(T_b), \tag{11}$$

while the material entrainment rate at $\bar{V}_\infty < 0.3 \cdot 10^{-3}$ m/sec can be estimated from the expression

$$G_{\Sigma} \approx \frac{q'_m}{6{,}79\,\bar{c}_p\,(T_w - T_0)}. \tag{12}$$

Therefore, for instance, the denominator in (12) is also approximately equal to twice the heat of material evaporation for vitreous materials with a surface temperature equal to the boiling temperature under atmospheric pressure conditions.

According to the JANAF thermodynamic tables, the maximal value of thermal sublimation effect for carbon reaches ~ 28,000 kJ/kg. Processing the experimental data [9], presented in Fig. 4, at the surface temperatures corresponding to the sublimation destruction regime ($T_w > 3300$°K) by least squares yields a value of 58,680 kJ/kg for H which exceeds $2\Delta Q_{ph}$ by 5% and is practically equal to 6.79 H(T) at the carbon melting point of 4130°K [11].

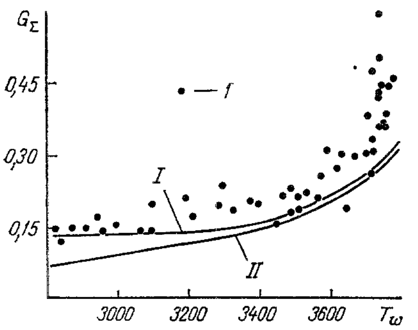

Fig. 5. Dependence of the mass entrainment rate for graphite on the surface temperature: I) computation by the method in [2]; II) computation by (10); 1) experiment [9] for $P_e \approx 1\cdot10^5$ Pa; $(\alpha/c_p)_0 = 1$ kg/m²·sec ± 30%. G_Σ, kg/m²·sec; T_w, K.

However, it is mentioned in [7] that as the quantity of atoms increases per molecule of substance, a computation using (11) will differ more and more from the true value of the heat of evaporation. For instance, the heat of polytetrafluorethylene decomposition is considerably less than the quantity $3.4H(T_d)$. Nevertheless, the parameter H can be taken equal to $2\Delta Q_{ph}$ even in this case. A comparison of the quantity H obtained by least squares with the heat of phase transition for the materials considered is shown in the table.

It should be noted that in analyzing the results only those experimental data were taken into account for which the enthalpy drop was greater than the minimal attainable value of $I_e - I_w$ that satisfies (10) for a positive value of $\bar{G}'_\Sigma$.

Since the experimental values of G'_Σ are in agreement with not only the computation by means of (10) but also by means of (2) and (3) upon substitution of the maximal value of ΔQ_w and $\Gamma = 1$ (Fig. 4, curves II), then $\bar{G}'_\Sigma$ should apparently be understood as that dimensionless mass entrainment rate that the material has when its "thermodynamic possibilities" are realized completely under the given external conditions. Values of H(T) from [11] were substituted in (2) and (3) in place of $\bar{c}_p(T_w - T_0)$ for a certain rise in the accuracy of the computations. The dependence of the silicon dioxide heat content on the temperature presented in this table for the 2000-4000°K temperature range can be approximated with good accuracy by a polynomial of second degree $H(T) = 3.046\cdot10^{-8}T^2 + 1.390T - 503$, kJ/kg.

Shown in Fig. 5 is a comparison of the computation of the mass entrainment rate for graphite by means of (4)-(7) and (10) for $P_e = 0.98\cdot10^5$ Pa and $(\alpha/c_p)_0 = 1$ kg/m²·sec. An experimental dependence of the graphite surface temperature on the stagnation enthalpy (see Fig. 3, points 4), constructed from data in [9], was used in the computation by means of (10). The computation using (10) is in good agreement with the computation by the method in [2] on the sublimation section.

Despite the fact that the stagnation pressure varied by an order in the experiments, and the heat-transfer coefficient by 5 times, their influence on the dimensionless entrainment rates $\bar{G}_\Sigma$ and $\bar{G}'_\Sigma$ could not be detected successfully. The influence of the change in P_e and $(\alpha/c_p)_0$ in the mentioned range on the dimensionless entrainment rate is probably within the limits of experiment error. It is noted in [1] that the dimensionless destruction rate $\bar{G}_\Sigma$ depends only on the stream stagnation enthalpy and is practically independent of the coefficient $(\alpha/c_p)_0$. The nonequilibrium of the process and the heat elimination from the surfaces by radiation start to be influential only in the low pressure domain. Comparative computations showed that the regularities noted are conserved even when considering $\bar{G}_\Sigma$. The influence of the pressure on the $\bar{G}'_\Sigma$ of quartz glass is 30% less on the average than on $\bar{G}_\Sigma$. These computations also permit making the deduction that a change in P_e and $(\alpha/c_p)_0$ does not alter the linear nature of the dependence $\bar{G}'_\Sigma = f(\sqrt{I_e - I_w})$ and the magnitude of the parameter H.

Taking the above into account, we represent (2) in the form

$$\bar{G}'_\Sigma = \left\{ \frac{(1-\gamma\bar{G}'_\Sigma)(I_e - I_w) + 0{,}3\,[\Delta Q_{ph} + H(T_w)] - \overline{\varepsilon\sigma T_w^4}}{[\Delta Q_{ph} + H(T_w)]\sqrt{I_e - I_w}} \right\} \sqrt{I_e - I_w} - 0{,}3. \tag{13}$$

Hence, we can write for H

$$H = \left\{ \frac{[\Delta Q_{ph} + H(T_w)]\sqrt{I_e - I_w}}{(1-\gamma\bar{G}'_\Sigma)(I_e - I_w) + 0{,}3\,[\Delta Q_{ph} + H(T_w)] - \overline{\varepsilon\sigma T_w^4}} \right\}^2. \tag{14}$$

Here $\overline{\varepsilon\sigma T^4_w} = \varepsilon\sigma T^4_w/(\alpha/c_p)_0$, kJ/kg is the reduced radiation energy.

Computations using (14) for quartz glass in the 10^4-10^6 Pa pressure band and by using the surface temperatures from [1] show that the difference of the parameter H from $2\Delta Q_{ph}$ does not exceed ±5% for $I_e > 15{,}000$ kJ/kg.

Since $\bar{G}'_\Sigma \to \bar{G}_\Sigma$ while $\sqrt{I_e - I_w} \to \sqrt{I_e}$ (Figs. 2 and 4) as the stagnation enthalpy increases, then a dependence of the form

$$\bar{G}_\Sigma \approx \left(\frac{I_e}{H}\right)^{0,5} - 0.3$$

can be recommended to estimate the rate of destruction of new materials for large values of I_e. In a first approximation H can be determined by knowing the class of material and its composition.

Therefore, the parameter H should apparently be considered the heat of material destruction under unilateral heating conditions. In contrast to the effective enthalpy it is practically independent of the external conditions and the material gasification coefficient and approximately equals $2\Delta Q_{ph}$.

NOTATION

$\bar{V}_\infty$, G_Σ, linear and mass rates of material destruction; $\bar{G}_\Sigma$, $\bar{G}'_\Sigma$, dimensionless mass entrainment rates; G_w, dimensionless evaporation rate; $(\alpha/c_p)_0$, heat-transfer coefficient; γ, blowing parameter; I_e, P_e, free gas stream stagnation enthalpy and pressure; T_w, T_0, surface and unheated material temperatures; I_w, $I_{c.w.}$, gas enthalpy at the material surface and calorimeter temperatures; Γ, gasification coefficient; $\bar{c}_p$, mean integral specific heat; ε, emissivity; σ, Stefan–Boltzmann constant; ΔQ_w, thermal effect of the total physicochemical transformations on the surface; ΔQ_e, heat of evaporation; T_{ph}, ΔQ_{ph}, phase transition temperature and thermal effect; T_b, T_d, boiling point and material decomposition temperature; $\bar{c}_{c,w}$, carbon concentration; $G_w^{(D)}$, $G_w^{(S)}$, diffusion combustion and sublimation rates; R, radius of hemispherical bluntness; R_{ef}, effective radius of the model; q_m', mean-integral heat flux; H(T), H, heat content and heat of material destruction; σ', rms deviation.

LITERATURE CITED

1. Yu. V. Polezhaev and F. B. Yurevich, Heat Shield [in Russian], Moscow (1976).
2. S. M. Scala and L. M. Gilbert, AIAA J., 3, No. 9, 87-100 (1965).
3. G. A. Frolov, Inzh.-Fiz. Zh., 50, No. 4, 629-635 (1986).
4. G. A. Frolov, A. A. Korol', V. V. Pasichnyi, et al., Inzh.-Fiz. Zh. (in press).
5. O. A. Sergeev, A. G. Shashkov, and A. S. Umanskii, Inzh.-Fiz. Zh., 43, No. 6, 960-970 (1982).
6. F. B. Yurevich, Heat and Mass Transfer and Thermal Properties of Materials [in Russian], Minsk (1969), pp. 145-154.
7. G. A. Frolov, V. V. Pasichnyi, Yu. V. Polezhaev, et al., Inzh.-Fiz. Zh., 50, No. 5, 709-718 (1986).
8. V. V. Kuzmich, Features of Heat and Mass Transfer Processes [in Russian], Minsk (1979), pp. 194-197.
9. Lundell and Dickey, AIAA J., 11, No. 2, 111-119 (1973).
10. G. A. Frolov, V. V. Pasichnyi, V. S. Dvernyakov, and K. B. Isaev, Inzh.-Fiz. Zh., 42, No. 5, 792-798 (1982).
11. Thermodynamic Properties of Individual Substances (Handbook) [in Russian], 4 vols., Moscow (1979-1982).