INFLUENCE OF THERMAL CONDUCTIVITY OF A MATERIAL ON AN UNSTEADY HEAT REMOVAL PARAMETER

Yu. V. Polezhaev and G. A. Frolov

UDC 536.2.083

In preparing [1] the authors additionally studied the influence of the thermophysical properties of a material on its unsteady breakdown. They found that the unsteady heat removal parameter d_0 depends logarithmically on the thermal conductivity.

The complexity and diversity of the physical and chemical processes accompanying unsteady breakdown of the surface of a material make it practically impossible to compute the recession rate and the thickness removed. For this calculation we need a large set of thermophysical and kinetic characteristics, the definition of each of these being a complex independent problem. However, we have developed a reliable method of determining the quasisteady mass recession rate, based on experimental determination of the effective enthalpy of the thermal protection material [2].

In [1] we proposed a new parameter d_0 describing the unsteady time to break up a material, to be used with a known quasisteady recession rate and analytical relationships to calculate linear recession and its rate in an unsteady surface breakdown regime:

$$S(\tau)/S(\tau_v) = \left[\frac{\sqrt{\tau} - \sqrt{\tau_r}}{\sqrt{\tau_v} - \sqrt{\tau_r}}\right]^2, \tag{1}$$

$$\tau_v = \frac{K_{Tb}^2 - 1}{K_{Tb}^2}\frac{d_0}{\bar{V}_\infty} = 2{,}83\frac{d_0}{\bar{V}_\infty}, \tag{2}$$

$$S(\tau_v) = d_0/K_{Tb}^2. \tag{3}$$

Figure 1 shows the computed mass recession for a model of quartz glass melting [2], and this practically coincides with that computed from Eq. (1), if Eqs. (2) and (3) are used to determine the time τ_v and the linear recession $S(\tau_v)$.

On the basis of experiment and theory it was shown in [1] that the parameter d_0 depends weakly on the heating conditions and all the properties of the material except its thermal conductivity. However, the investigations in [1] were carried out with a heat transfer coefficient close to 1, while the thermal conductivity varied in the range 1.7-4.2 W/(m·K).

The aim of the present paper is to determine how the unsteady recession parameter d_0 depends on the material thermal conductivity over a wide range of external heating conditions.

The computations were carried out on a model of quartz glass fusion described in [2]. Here the heat transfer coefficient $(\alpha/c_p)_0$ was 0.5 kg/(m^2·sec), the stagnation pressure was $P_e = 0.13 \cdot 10^5$ Pa, and the stagnation temperature was $T_e = 6000$ K. In the computations we considered the kinetic curves $S(\tau)$ and $V_\infty(\tau)$ obtained by varying the thermal conductivity from 2 to 13 W/(m·K). The calculations shown in Table 1 were performed with $\Delta Q_w = 12{,}570$ kW/kg, $\varepsilon\sigma T_w^4 = 250$ kW/m^2, $\tilde{M}_v = 0.57$, $\gamma = 0.66$. The drop of enthalpy in the boundary layer was determined from the formula $I_e - I_w = a\sqrt{T_e - T_w}$, where $a = 265.4$ kW/(kg·K).

Institute for High Temperatures, Academy of Sciences of the USSR, Moscow. Institute for Development of Materials, Ukrainian Academy of Sciences, Kiev. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 62, No. 4, pp. 546-551, April, 1992. Original article submitted August 6, 1991.

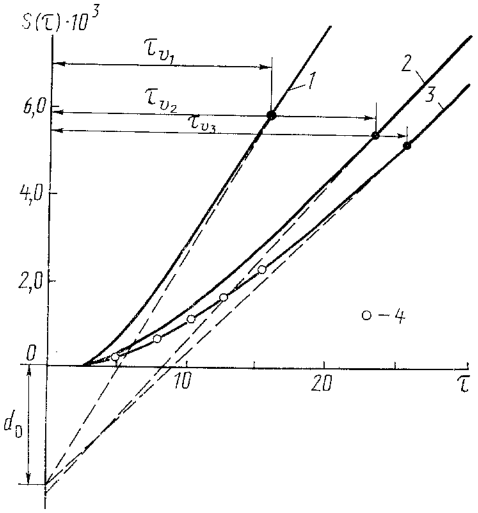

Fig. 1. The linear recession of quartz glass as a function of heating time: 1-3) computed for options 4, 6, 7 (Table 1) on the quartz glass fusion model described in [1], and Eqs. (1)-(3); 4) experiment of [4]. $S(\tau)$, m; τ, sec.

First we turn to the value of d_0 obtained for options 1 and 2. These options were computed for close values of λ, ρ, c_p, and the values of d_0 found agree with the value determined at the same temperature, for stagnation pressure $1\cdot 10^5$ Pa and for $(\alpha/c_p)_0 = 1$ kg/(m^2·sec) in [1]. Therefore, reducing the stagnation pressure by an order of magnitude has practically no influence on the parameter d_0.

TABLE 1. Results of Determining the Unsteady Recession Parameter d_0 for the Theoretical Kinetic Curve $S(\tau)$ for $T_e = 6000$ K; $P_e = 0.13\cdot 10^5$ Pa; $(\alpha/c_p)_0 = 0.5$ kg/(m^2/sec)

Computed option	λ, W/(m·K)	c_p, kJ/(kg· K)	ρ, kg/m^3	$\bar{V}_\infty\cdot 10^3$, m/sec	T_w, K	$d_0\cdot 10^3$, m
1	2,0	1,05	2245	0,285	2651	0,9
2*)	2,1	1,13	2200	0,27	2664	0,8
3	6,3	3,11	2400	0,225	2595	2,0
4	8,0	2,93	2245	0,28	2585	2,25
5	10,5	1,38	2245	0,55	2587	2,85
6	10,5	1,38	2245	0,365	2623	3,1
7	10,5	1,38	2245	0,31	2630	2,9
8	12,6	1,26	2240	0,32	2637	3,2

---

*This option computed for $T_e = 6100$K.

In options 5-7 we varied substantially the dependence of viscosity on temperature. Figure 2 compares the different slopes of the viscosity variation. It can be seen from Table 1 that the variation of the law of temperature dependence of viscosity has a weak influence on the parameter d_0. These data confirm the conclusion reached in [1] that there is a weak influence of material properties on d_0, and that we can turn to analysis of its dependence on thermal conductivity as shown by the computed and experimental data.

The experimental values of d_0 obtained in [1] were added to the investigations of materials with higher thermal conductivity and the results of analysis of the kinetic curves $S(\tau)$ presented in [3-5]. In [3] a linear recession of clear plastic with epoxy bond was found by three methods: by visual adjustment of the position of the end of the specimen from a ×5 magnified screen image (as the specimen burned it was fed in by means of an electric motor), by a copy of the measurements on a recording screen of electric sensor readings on a drift oscillograph, and by direct measurement of the specimen length

TABLE 2. Results of an Experimental Determination of the Parameter d_0 under Various Heating Conditions

Regime number	Material	q, kW/m²	T_w, K	$\overline{V}_\infty \cdot 10^3$, m/sec	$d_0 \cdot 10^3$, m	$d_0^a \cdot 10^3$, m
1	Alloyed ceramic (0,5% Cr_2O_3)	4130	2350	0,02	0,4	0,31± ±30%
2		7260	2400	0,05	0,4	
3		7650	2620	0,1	0,26	
4		11500	2800	0,18	0,29	
5		14000	2820	0,21	0,26	
6		14700	2500	0,18	0,41	
7		50000	≃3000	0,91	0,23	
8	Graphite	52000	—	1,0	4,5	4,5
9		90850*)	3440	1,46	4,55	
10		113600*)	3440	3,5	4,45	
11	Alumina	1000	—	0,44	3,3	
12	Teflon	20000	1000	0,72	0,27	
13	pure ceramic	7650	2620	0,17	0,85	
14		11500	2710	0,29	1,13	
29	quartz glass	7650	2590	0,22	1,35	
30		7600**	2700	0,31	2,45	

---

*Data of [5].

**Data of [4].

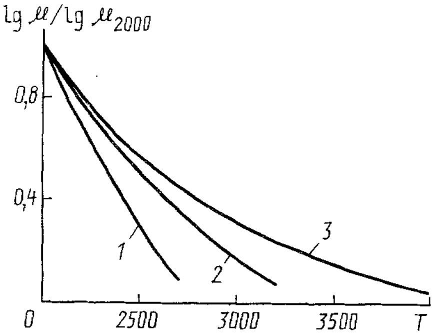

Fig. 2. Comparison of different slopes of variation of viscosity with temperature, assumed in computing the options of Table 1: 1) options 1-4, 8 – $\mu = \exp[68{,}800/T_w - 24.59]$; 2) option 6 – $\mu = \exp[50{,}500/T_w - 15.0]$; 3) option 7 – $\mu = 9.8\exp[\exp(1180/T_w + 10.05)/T_\omega - 9.5]$. T, K.

at the time of the test. In spite of the fact that in the experiments the stagnation enthalpy was in the range 16,000-43,000 kJ/kg, and the heat transfer coefficient was a factor of 2 less compared with the conditions of [1], the deviation of values of d_0 did not exceed 25%.

As can be seen from Table 2, supplementing the data of [1], for nontransparent materials the parameter d_0 depends weakly on the heating conditions. The substantial scatter of the experimental data for the alloyed ceramic can be explained to some extent by the strong dependence of the thermal conductivity of this material on the technical conditions of manufacture. According to [6], λ depends not only on the final porosity of the specimens, which differs by 10-12% for the experiments, but also on the porosity of the stock prior to sintering. Since the specimen diameter for the different experimental facilities varied from $10 \cdot 10^{-3}$ to $25 \cdot 10^{-3}$ m, they could not be prepared in one batch, and some scatter in their thermal conductivity is possible.

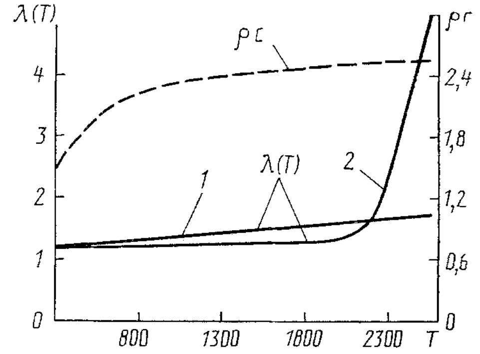

Fig. 3. Thermophysical properties of alloyed (1) and pure (2) quartz ceramic; ρc from the data of [12], λ(T), W/(m·K); ρc, kJ/(m³·K).

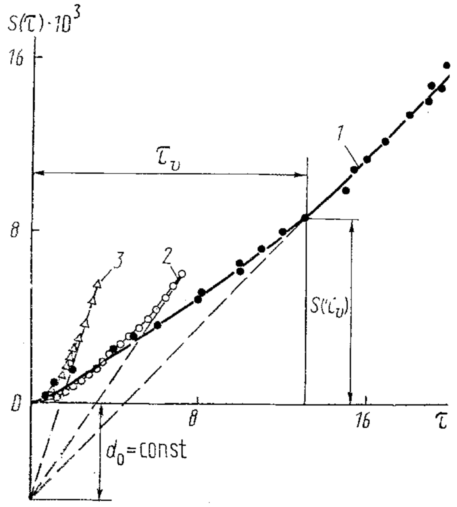

Fig. 4. Dependence of linear recession S(τ) of graphite on heating time in the pressure range (1.5-50)·10⁵ Pa; 1) q = 52,000 kW/m², I_e = 42,000 kW/kg, P_e = 1.54·10⁵ Pa, $\bar{V}_\infty$ = 1·10⁻³ m/sec; 2,3) data of [5], 2) q = 90,850 kW/m², I_e = 16,300 kJ/kg, P_e = 25·10⁵ Pa, $\bar{V}_\infty$ = 1.46·10⁻³ m/sec; 3) q = 113,600 kW/m², I_e = 11,500 kW/kg, P_e = 50·10⁵ Pa, $\bar{V}_\infty$ = 3.5·10⁻³ m/sec.

A strong dependence of the parameter d_0 on the radiative heat transfer component, the surface temperature, and the recession rate is observed for the semi-transparent materials (pure ceramic at temperatures above 1800 K, and quartz glass), and this prevents us at present from drawing a definite conclusion as to the nature of the dependence. The sharp increase of transparency of the pure quartz ceramic at temperatures above 1800 K leads to a strong increase in the thermal conductivity due to the radiative component of the heat transfer (Fig. 3), and to the complex form of the dependence on the conditions at the receding surface. Figure 3 shows the temperature dependence of thermal conductivity of the pure and the alloyed ceramic, which for temperatures up to 1800 K were determined using inverse thermal conduction theory [7] and the temperature fields obtained in [8]. In the temperature range 1800 K to K − T_w for the alloyed ceramic the values of λ(T) were found from the measured quasisteady values of heated layer thickness up to the isotherm T^* = 1800 K, corresponding to a color change [9]. The effective thermal conductivity of the pure ceramic in this temperature range was determined by matching the thermal conductivity equation, allowing for surface mass recession computed using the parameter d_0 and the experimental dependence of T_w. It should be noted that for materials exhibiting a sharp transition at high temperatures from the practically non-transparent zone to the semi-transparent, this method of determining λ(T) is evidently at present the only possible one, since

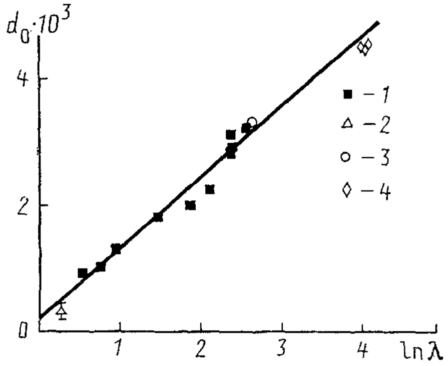

Fig. 5. Dependence of the unsteady recession parameter d_0 on the logarithm of thermal conductivity: 1) as computed in the quartz glass fusion model [2]; 2) alloyed quartz ceramic; 3) alumina; 4) graphite. d_0, m.

we cannot mount thermocouples in the high-temperature semi-transparent zone, where there are large errors in temperature measurement [10, 11].

There is a special interest in determining the unsteady recession parameter for graphite. It can be seen from Fig. 4, that the variation of the recession rate in the range $(1\text{-}3.5)\cdot 10^{-3}$ m/sec and the strong difference in the heating conditions practically do not change the value of d_0. As one might expect, because of the very high thermal conductivity it has the largest value of all the classes of material examined.

The experimental values of d_0 for alumina and graphite, referenced to a thermal conductivity at $T' = (T_w + T_0)/2$, and the computed values for constant thermophysical properties, as shown in Fig. 5, are satisfactorily described by the expression $d_0 = (1.13 \ln\lambda + 0.2)\cdot 10^{-3}$ m, where λ, W/(m·K).

Thus, the computed and experimental results show a specific influence of the thermal conductivity of the material on the unsteady recession parameter d_0 and indicate that it could be used to compute unsteady recession instead of thermal conductivity, which is difficult to determine at high temperatures.

NOTATION

d_0, unsteady recession parameter; $V_\infty(\tau)$, $\bar{V}_\infty$, recession rate and its quasisteady value; τ, heating time; τ_v, time to establish a quasisteady recession rate; τ_r) time of start of recession; $S(\tau)$, $S(\tau_v)$, linear recession and its value at the end of the unsteady period; K_{T_b}, material breakdown constant; λ, thermal conductivity; c_p, heat capacity; ρ, density; λ(T), ρc(T), temperature dependence of thermal conductivity and volume heat capacity; $(\alpha/c_p)_0$, heat transfer coefficient; T_e, P_e, stagnation temperature and pressure; ΔQ_w, total thermal effect of the physical and chemical transformation on the surface; ε, emissivity; σ, Stefan–Boltzmann constant; T_w, surface temperature; $\bar{M}$, molecular weight of the vapors; γ, blowing parameter; I_e, stagnation enthalpy; I_w, enthalpy of the gas at the surface temperature; μ, viscosity; q, heat flux.

LITERATURE CITED

1. Yu. V. Polezhaev and G. A. Frolov, Inzh.-Fiz. Zh., **56**, No. 4, 533-539 (1989).
2. Yu. V. Polezhaev and F. B. Yurevich, Thermal Protection [in Russian], Moscow (1976).
3. V. L. Sergeev, Unsteady Heat and Mass Transfer near the Stagnation Point [in Russian], Minsk (1988).
4. M. C. Adams, W. E. Powers, and S. J. Georgiev, J. Aerosp. Sci., **27**, No. 7, 535-547 (1960).
5. R. A. Williamson, W. A. Rinehart, and R. R. Williams, J. Spacecraft and Rockets, **10**, No. 10, 1-6 (1973).
6. E. I. Suzdal'tsev, Izv. Akad. Nauk SSSR, Neorg. Mater., **20**, No. 2, 330-335 (1984).
7. P. V. Prosuntsov, S. V. Reznik, and G. A. Frolov, Thermophysical Properties of Substances: Rep. VIII All-Union Conf., Novosibirsk (1988), p. 118.

8. G. A. Frolov, V. V. Pasichnyi, E. I. Suzdal'tsev, and V. S. Tsyganenko, Inzh.-Fiz. Zh., **57**, No. 2, 313-318 (1989).
9. G. A. Frolov, A. A. Korol. V. V. Pasichnyi et al., Inzh.-Fiz. Zh. **51**, No. 6, 932-940 (1986).
10. V. N. Eliseev and V. A. Solovov, Heliotekhnika, No. 6, 45-49 (1983).
11. A. M. Mikhalev and S. V. Reznik, Izv. Vyssh. Uchebn. Zaved., No. 4, 55-59 (1988).
12. R. E. Krzhizhanovskii and Z. Yu. Shteri, Thermophysical Properties of Nonmetallic Materials (Oxides) [in Russian], Leningrad (1973).

DETERMINATION OF QUASISTATIONARY MATERIAL SURFACE DESTRUCTION RATE FROM LINEAR ENTRAINMENT MEASUREMENTS IN THE NONSTATIONARY REGIME

G. A. Frolov, A. V. Bondarenko,
V. V. Pasichnyi, and N. E. Aleksandrova

UDC 536.2.083

A method is proposed for determining the quasistationary linear entrainment rate $\bar{V}_\infty$ and the nonstationary entrainment parameter d_0 from measurements of the thickness of the entrained layer during the nonstationary period of the destruction of the surface of a material.

One of the most important characteristics of a heat-shielding material is the rate of destruction of its surface during interaction with a high-temperature medium [1]. It is especially important to determine the quasistationary entrainment rate $\bar{V}_\infty$, which it is necessary to know in order to calculate the effective enthalpy and to compare different materials with one another. Moreover, as shown in [2], the rate $\bar{V}_\infty$ must be achieved in order to determine the nonstationary entrainment parameter d_0, which in some cases makes it possible to calculate nonstationary mass entrainment without the use of high-temperature thermophysical characteristics.

During experiments it may happen that the apparatus does not operate long enough in order for a quasistationary rate $\bar{V}_\infty$ to be established. In this case the equations derived in [2] on the basis of the destruction constant K_{T_d} and the nonstationary entrainment parameter d_0

$$S(\tau) = \left(\frac{\sqrt{\tau} - \sqrt{\tau_\mathrm{ent}}}{\sqrt{\tau_v} - \sqrt{\tau_\mathrm{ent}}}\right)^2 S(\tau_v), \tag{1}$$

$$\tau_v = \frac{K_{T\mathrm{d}}}{1 - K_{T\mathrm{d}}} \frac{d_0}{\bar{V}_\infty} = 2{,}83 \frac{d_0}{\bar{V}_\infty}, \tag{2}$$

$$S(\tau_v) = \frac{2K_{T\mathrm{d}} - 1}{1 - K_{T_\mathrm{d}}} d_0 = 1{,}83 d_0, \tag{3}$$

suggest a method for determining the quasistationary entrainment rate and the parameter d_0 itself.

Institute of Problems in Material Science, Academy of Sciences of Ukraine, Kiev. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 62, No. 4, pp. 552-554, April, 1992. Original article submitted August 6, 1991.

1062-0125/92/6204-0396$12.50