EFFECT OF THE TYPE OF HEATING ON THE RATE OF DESTRUCTION OF MATERIALS

G. A. Frolov

UDC 536.212.3

An experimental determination is made of the dependence of the gasification parameter and effective enthalpy on stagnation enthalpy and the fraction of the radiant component of a heat flow.

In the high-temperature heating of thermally protective materials, the supplied heat is accumulated by the material, radiated from the heated surface, absorbed in phase and physicochemical transformations, and reduced by the injection of gaseous disintegration products into the boundary layer. The quantity of heat absorbed as a result of the thermal effects of phase transformations and injection depends to a considerable degree on the gasification parameter Γ. This parameter is the fraction of gaseous disintegration products in the total mass of material removed [1]:

$$\Gamma = \frac{G_w}{G_\Sigma}. \tag{1}$$

According to [1], the ablation rate on the surface in a quasisteady regime of disintegration can be found from the heat balance equation

$$\rho \bar{V}_\infty = \frac{q_0}{\Gamma [\Delta Q_w + \gamma (I_e - I_w)] + \bar{c}_p (T_w - T_0)}. \tag{2}$$

In studies of materials in high-temperature jets, the heat flow to the intact part of the surface q_0' is often calculated by means of a relation obtained with the assumption of equality of the heat-transfer coefficients on cold and hot surfaces:

$$q_0' = q_c \frac{I_e - I_w}{I_e - I_{x.st}} - \varepsilon \sigma T_w^4. \tag{3}$$

The denominator of (2) is called the effective enthalpy of the disintegrating material and is determined from the formula

$$I_{ef} = \frac{q_0 - \varepsilon \sigma T_w^4}{\rho \bar{V}_\infty} \tag{4}$$

or, if the values of Γ and ΔQ_w are given, from the relation

$$I_{ef} = \Gamma [\Delta Q_w + \gamma (I_e - I_w)] + \bar{c}_p (T_w - T_0). \tag{5}$$

The pattern of disintegration of the material becomes clearer if we know the contribution to I_{ef} of thermal effects of phase and physicochemical transformations, the effect of injection, and the heat content (specific heat). However, the possibility of directly measuring the gasification parameter Γ is extremely limited.

To experimentally determine the parameter Γ in this study, we examined pure and alloyed quartz glass-ceramics in a subsonic stream in an electric-arc heater [2], on a unit which provides simultaneous radiative and convective heating [3], and in the supersonic jet of a gas generator operating on kerosine–oxygen fuel. The test regimes are shown in Table 1. In tests in these regimes, the film of molten material flowing from the surface hardened on the edges of the specimen (see Fig. 1). Weighing of the specimens with and without the film allowed us to determine the rate of vaporization and the gasification coefficient.

The accuracy of the given method is determined to a significant extent by the amount of material carried off by the gas flow in the liquid or solid state. However, the results of

Institute of Problems of Materials Science, Academy of Sciences of the Ukrainian SSR, Kiev. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 50, No. 4, pp. 629-635, April, 1986. Original article submitted January 28, 1985.

0022-0841/86/5004-0448 $12.50

TABLE 1. Test Regimes for Specimens of the Materials

Regime	q_c	q_r	I_e	$P_e \cdot 10^{-5}$	$(\alpha/c_p)_e$
1	2000	—	4100	1,006	0,55
2	4500	—	7400	1,012	0,65
3	6000	—	7400	1,028	0,86
4	10500	—	10600	1,045	1,03
5	14000	—	12300	1,054	1,18
6	14000	—	15000	1,034	0,96
7	19500	—	15400	1,063	1,3
8	10500	5200	12300	1,028	0,89
9	10500	10500	12300	1,028	0,89
10	14000	10500	15000	1,034	0,96
11	14700	—	13000	0,34	1,17
12	14700	—	4700	3,5	3,34
13	—	14700	—	1,0	—

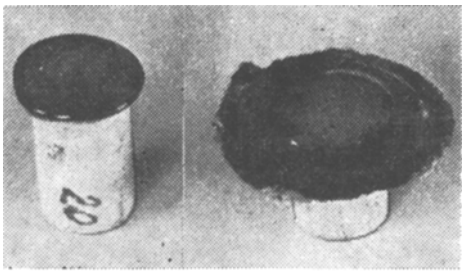

Fig. 1

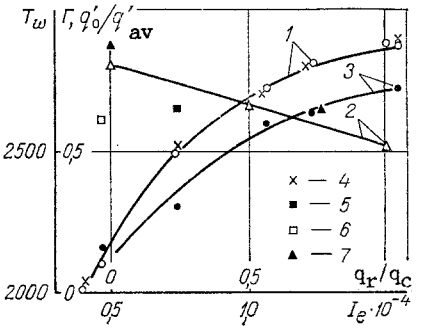

Fig. 2

Fig. 1. Specimens of alloyed quartz glass-ceramic after tests in a subsonic flow.

Fig. 2. Dependence of the gasification parameter Γ on stagnation enthalpy (1) and the fraction of the radiant component of heat flux (2) in comparison to the ratio of the heat fluxes q_0'/q_{av}' (3); 2, 7) the gasification parameter at I_e = 12,300 and 15,000 kJ/kg; 4-6) surface temperature; 4) regimes 1, 2, 4, 5, 7; 5) regime 3; 6) regime 12. T_w, K; I_e, kJ/kg.

tests of specimens in the jet of the gas generator (regime 12) show that the ablation by the gas flow is no greater than 10% even if we assume that Γ = 0 under these conditions. The dynamic pressure in the subsonic stream of the electric-arc heater was almost half as great as in the generator jet. Thus, it can be assumed that the high viscosity of the film of molten quartz glass-ceramic under such heating conditions practically eliminates separation of the film from the lateral surface of the specimen.

The gasification parameter was determined in the generator jet in the range of heating times 4-30 sec. Observation of the ablation process, inspection of the specimen surface after the test, and weighing of the specimens with and without the film of melt allowed us to conclude that no material is carried off by the gas flow on the specimens of pure glass-ceramic within the first 15 sec of heating. No separation of the film from the lateral surface of the specimens of alloyed glass-ceramic was seen over 30 sec of heating.

The numerical results in [11] show that the parameter Γ depends mainly on the stagnation enthalpy of the gas flow. A change in pressure from 10^3 to 10^6 Pa leads to a change in the parameter Γ by no more than 20%. In tests conducted to determine Γ, the stagnation pressure ranged from $1 \cdot 10^5$ to $3.5 \cdot 10^5$ Pa. Thus, its effect can be ignored. Let us see the degree to which Γ depends on the stagnation enthalpy and the surface temperature of the material.

It is evident from Fig. 2 (point 4) that the surface temperature may be a monotonic function of the stagnation enthalpy in the subsonic stream of the electric-arc heater (regimes 1, 2, 4, 5, 7). At the same time, an increase in the heat flow due to the heat-transfer coefficient (regimes 3 and 12), given the same stagnation enthalpy, leads to a substan-

TABLE 2. Comparison of Experimental and Theoretical Rates of Linear Ablation of a Quartz Glass-Ceramic ($\rho \approx 2000$ kg/m^3)

Heating regime	Glass-ceramic	T_w	ε	q_0'	q_{av}'	q_0'/q_{av}'	Γ	$\bar{V}_\infty \cdot 10^3$	
								expt.	calc.
3	Alloyed	2650	0,83	1220	4190	0,29	0,49	0,08	0,063
4		2710	0,83	4910	8340	0,59	0,72	0,16	0,17
5		2820	0,83	7240	11370	0,64	0,81	0,21	0,22
7		2900	0,83	11800	16480	0,72	0,87	0,3	0,31
8		2840	0,83	8920	—	—	0,66	0,28	0,32
9		2840	0,83	13320	—	—	0,52	0,5	0,57
12		2610	0,75	1520	9360	0,16	0,1	0,19	0,18
6	Pure	2840	0,64	8560	11900	0,72	0,88	0,25	0,23
10		2840	0,64	15280	—	—	0,67	0,46	0,5

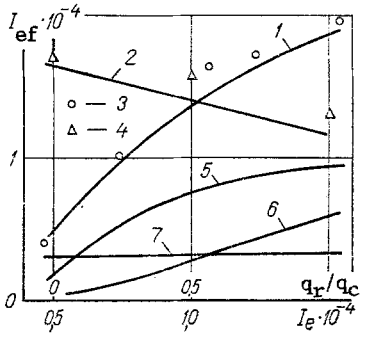

Fig. 3. Dependence of the effective disintegration enthalpy and its components on stagnation enthalpy and the fraction of the radiant component of heat flux: 1-4) effective enthalpy; 1, 2) calculation by (5); 3, 4) calculation by (4); 2, 4) I_e = 12,300 kJ/kg, regimes 5, 8, 9; 1, 3) regimes 3-5, 7, 12; 5) $\Gamma \Delta Q_w$; 6) $\Gamma \gamma (I_e - I_w)$; 7) $c_p(T_w - T_0)$. I_{ef}, kJ/kg.

tial increase in the temperature of the specimen surface (points 5 and 6). Thus, in the supersonic jet of the gas generator (regime 12) it is roughly 600°K higher than in regime 1. Since the parameter Γ increases monotonically with an increase in stagnation enthalpy under all of the heating conditions examined (curve 1), its effect is evidently greater than the effect of surface temperature and heat flux.

To determine the dependence of the parameter Γ on the fraction of the radiant component of the heat flux, specimens of glass-ceramic were tested at constant surface temperatures and stagnation enthalpies (regimes 5, 6, 8-10). As was shown in [4], surface temperature remains nearly constant with an increase in the fraction of the radiant component if $q_c > q_r$. It is evident from Fig. 2 (curve 2 and points 7) that Γ decreases in proportion to the increase in the radiant component. This apparently occurs as a result of a decrease in the temperature gradient at the surface and the consequent removal of more material from the melt film. The moderate increase in Γ for the specimens of pure glass-ceramic (points 7) is due to the higher stagnation enthalpy (regimes 6 and 10).

Table 2 shows experimental values of the rate of disintegration of specimens of a quartz glass-ceramic and values calculated from Eq. (2). At least 10 specimens were tested in each regime. The empirical data was analyzed statistically. In the calculation, we used values of emissivity from [4] and data on specific heat from [5]. We took a mean-integral specific heat of 1.3 kJ/kg·K for all of the heating regimes. According to [1], the total thermal effect for glassy materials changes relatively little and for quartz glass may be taken as about 11,000 kJ/kg. It can be seen from the table that the experimental and calculated disintegration rates agree with each other to within 15%, which is no greater than the experimental error. The data obtained confirms the adequate accuracy of the experimental values for the gasification parameter and allows us to determine all components of the effective enthalpy.

The effective enthalpy was calculated both from Eq. (4) (points 3 and 4 in Fig. 3) and from (5) (curves 1 and 2). As the parameter Γ, the effective enthalpy monotonically decreases with an increase in stagnation enthalpy. Here, the change in heat flux due to the heat-transfer coefficient does not alter the character of this relation. The identical form of the relations for effective enthalpy and the gasification parameter can be explained if we examine the contribution of heat content, the thermal effect of phase and physico-

TABLE 3. Parameters of the Disintegration of a Glass-Plastic on an Epoxy Binder and Asbestos–Textolite with q_c = (1.4÷1.47)·10^4 kW/m^2 under Different Heating Conditions

Heating regime	Type of heating	P_d	Glass-plastic			Asbestos–textolite		
			T_w	$\bar{V}_\infty \cdot 10^3$	I_{ef}	T_w	$\bar{V}_\infty \cdot 10^3$	I_{ef}
13	Radiative	~0	2860	0,45	11 000	3060	0,17	30500
5	Subsonic air stream	5400	2690	0,5	10 000	3060	0,33	11200
11	Supersonic air jet	34 000	2550	0,56	10 500	2850	0,45	11500
12	Supersonic jet of combustion products (α = 1,2)	250 000	2380	0,45	4 800	2380	0,6	3900

chemical transformations, and injection to effective enthalpy. It is evident from Fig. 3 that heat content remains nearly constant throughout the investigated range of stagnation enthalpy (curve 7). At the same time, the contribution of the heat of phase transitions increases with an increase in the gasification parameter (curve 5), while the contribution of injection increases with an increase in both the gasification parameter and stagnation enthalpy (curve 6). The results obtained show that the contribution of injection does not exceed 30% at stagnation enthalpies up to 15,000 kJ/kg.

We should point out that despite the roughly equal calorimetric heat flows and rates of disintegration of the specimens in regimes 5 and 12, their effective enthalpy and the quasisteady values of heat flux calculated from (3) differ by a factor of four. This difference is apparently not a random result, since the data in Table 3 shows that an increase in dynamic pressure from about 0 to 2.5·10^5 Pa and, thus, a change in the heat-transfer coefficient with a constant calorimetric heat flow also do not (within the experimental error) affect the rate of disintegration of a glass-plastic on an epoxy binder. The ablation rate for asbestos–textolite with a change in dynamic pressure in the above range changes several times, since the disintegration of this material is heavily dependent on the oxidizing and erosive-mechanical action of the incoming gas flow.

The effective enthalpy of both materials decreases sharply with a decrease in stagnation enthalpy (regime 12). However, if the velocity of the flow increases without a change in stagnation enthalpy, then the effective enthalpy also undergoes almost no change (regimes 5 and 11).

The heat flux delivered to the surface changes from q_c to q_0' during the time of temperature rise and subsequently remains constant. It is sometimes more convenient to compare q_0' not with the calorimetric heat flux but the mean integral heat flux during the period of time from 0 to τ_t (the time at which a quasisteady surface temperature is established). Oscillograms recording the increase in surface temperature during convective heating showed that the mean integral heat flux can be determined to within 2% by the following formula:

$$q'_{av} \approx \frac{q_c}{2}\left(1 + \frac{I_e - I_w}{I_e - I_{x.st}}\right) - \frac{1}{4}\varepsilon\sigma T_w^4. \qquad (6)$$

(In the experiments, the enthalpy of the gas at the temperature of the calorimeter surface $I_{x.st}$ averaged 450 kJ/kg.)

Since $(I_e - I_w)/(I_e - I_{x.st}) < 1$, it is evident from (3) and (6) that the greater the stagnation enthalpy, the less q_{av}' differs from q_0'. At the same time, an increase in stagnation enthalpy leads to an increase in the gasification parameter and, as follows from Fig. 2 (curves 1 and 3),

$$q_0'/q_{av}' \sim \Gamma. \qquad (7)$$

NOTATION

Γ, gasification parameter; G_w, vaporization rate, kg/(m^2·sec); G_Σ, ablation rate; ρ, density, kg/m^3; $\bar{V}_\infty$, quasisteady rate of linear ablation, m/sec; q_c, q_r, calorimetric con-

vective and radiant heat fluxes, kW/m^2; q_0, heat flux delivered to the heated surface, kW/m^2; q_0', heat flux delivered to the heated surface with allowance for the loss to radiation, kW/m^2; q_{av}', mean integral heat flux during the establishment of a constant surface temperature, kW/m^2; I_e, stagnation enthalpy of the gas flow, kJ/kg; P_e, stagnation pressure of the gas flow, Pa; I_w, $I_{x.st}$, enthalpy of the gas at the temperatures of the heated surface and calorimeter, kJ/kg; T_0, temperature of the material before heating, K; T_w, temperature of the surface being heated, °K; c_p, mean integral specific heat, kJ/kg·K; ΔQ_w, total thermal effect of the surface processes, kJ/kg; γ, injection parameter; ε, emissivity of the surface; σ, Stefan–Boltzmann constant, kW/(m^2·K^4); I_{ef}, effective disintegration enthalpy, kJ/kg; $(\alpha/c_p)_0$, heat-transfer coefficient, kg/(m^2·sec); P_d, dynamic pressure of the gas flow, Pa; α, oxidant excess coefficient.

LITERATURE CITED

1. Yu. V. Polezhaev and F. B. Yurevich, Thermal Protection [in Russian], Énergiya, Moscow (1976).
2. G. A. Frolov, V. S. Dvernyakov, V. V. Pasichnyi, and F. I. Zakharov, "Experimental study of heat transfer between subsonic and supersonic plasma jets and a flat surface," Inzh.-Fiz. Zh., 40, No. 6, 965-969 (1981).
3. G. A. Frolov, V. S. Dvernyakov, and V. V. Pasichnyi, "Some results of an experimental study of heat transfer on a surface under the combined influence of radiative and convective heat sources," Teplofiz. Vys. Temp., 16, 221 (1978). Submitted to VINITI, No. 4217-77 Dep.
4. G. A. Frolov, V. V. Pasichnyi, V. S. Dvernyakov, and K. B. Isaev, "Reflectivity of thermally protective materials with radiative–convective heating," Inzh.-Fiz. Zh., 42, No. 5, 792-797 (1982).
5. R. E. Krzhizhanovskii and Z. Yu. Shtern, Thermophysical Properties of Nonmetallic Materials (Oxides) [in Russian], Énergiya, Leningrad (1973).

INTERACTION OF THE ELECTRIC ARC IN A TWO-JET PLASMATRON WITH THE SURFACE OF A SOLID BODY

N. V. Livitan and S. P. Polyakov

UDC 533.9

The electrical and thermal characteristics of a magnetically controlled arc in a two-jet plasmatron interacting with a flat surface are presented.

Increased attention has been devoted in recent years to the problems of studying the interaction of concentrated energy fluxes with materials [1]. In many other energy sources, electric-arc plasmatrons, the thermal flux density from which and the nature of whose action on the surface being worked depend substantially on the structural peculiarities of the plasmatron and the conditions under which the electric arc burns, are widely used.

For example, the so-called indirect action plasmatrons, in which the electric arc burns between the cathode and the nozzle-anode, transferring heat to the plasma-forming gas blown past it, are characterized by a relatively low heat flux density of the order of 0.2-0.6 kW/cm^2 [2]. Moreover, the significant gas-dynamic head, characteristic for plasma jets, often also makes it difficult to use them.

The so-called direct-action plasmatrons, in which the electric arc burns directly between the cathode (or anode) of the plasmatron and the surface being worked, are distinguished by their high heat flux density in the substrate – up to 15-20 kW/cm^2 [3, 4]. At the location of fixing, however, the arc is, as a rule, contracted, which destroys the surface layer of the material being worked, and makes it difficult to work thin-walled structures and layers of protective coatings.

L. I. Brezhnev Dnepropetrovsk Metallurgical Institute.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 50, No. 4, pp. 635-640, April, 1986. Original article submitted December 5, 1984.

0022-0841/86/5004-0452 $12.50