A PARAMETER CHARACTERIZING THE EFFECT OF THERMOOPTICAL PROPERTIES OF A VITREOUS HEAT-SHIELD MATERIAL ON ITS RATE OF MELTING DUE TO RADIATIVE AND CONVECTIVE HEATING

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A parameter for assessment of the performance of a vitreous heat-shield material subjected to radiative and convective heating is proposed.

When radiation predominates in the heat flux, heat-shield materials (HSM) based on fused quartz are of great interest owing to their ability to reflect a considerable part of the incident radiation. For instance, tests of ultrapure fused quartz have shown that in the wavelength range 0.3-2.6 μm more than 80% of the incident radiation is reflected, and at a wavelength of 0.7 μm about 95% is reflected [1]. Materials of the quartz ceramic type are bulk-reflecting, since reflection does not take place at the surface, but is due to scattering of the radiation by optical inhomogeneities within the material. If the radiation mean free path is comparable with the thickness of the melt film, the rate of melting depends greatly on the thermooptical properties of the material [2, 3].

The thermooptical characteristics of a semitransparent material can be prescribed in the case of a spherical scattering indicatrix by three parameters: the refractive index n_r, the absorption coefficient α, and the scattering coefficient β. Calculations show that none of these parameters in itself is decisive for the rate of destruction.

For practical purposes, however, it is desirable to have a parameter that depends on the optical properties of the material and characterizes the performance of a particular HSM subjected to radiative and convective heating. To discover such a parameter we carried out calculations of the destruction of a vitreous HSM in the case of a hypersonic flow of air past a blunt body. The convective heat flux to the undamaged surface varied in the range 2.6-13.5 MW/m^2, and the incident radiation flux was 7.5-23.5 MW/m^2. The fraction of radiation in the total heat flux increased from 0.35 to 0.9, the refractive index varied from 1 to 2.3, the attenuation coefficient from 50 to 5000 m^{-1}, and the ratio of the scattering coefficient to the absorption coefficient from zero to 10^4.

A system of equations representing the destruction process was given in [3]; the method of solution was given in [4]. The mass evaporation rate was calculated from the Knudsen–Langmuir formula [5]. The boundary layer of gas was assumed to be transparent for radiation and in chemical equilibrium. The effect of injection of vapor on the convective heat transfer, friction, and mass transfer was taken into account by means of the relation in [6]. A comparison of the results of calculations by this approximate method with the results of numerical calculations [2] showed that in the case of a total heat flux of 8.2 MW/m^2 to the undamaged surface and a friction force gradient of 90 kN/m^3 at the critical point the difference in the mass melting rate did not exceed 15% when the radiation–conduction parameter $N = \gamma\lambda/4\sigma n_r^2 T_w^3$ was less than 0.5. When $N > 0.5$ the disagreement of the results increased to 23%. When the total heat flux was increased to 640 MW/m^2, the incident radiation flux to 580 MW/m^2, and the friction force gradient to 600 kN/m^3, the difference in melting rate did not exceed 10% for $N < 0.3$ and 36% for $N > 0.3$. The absorption coefficient in these calculations varied from 10^2-10^{-4} m^{-1}, and the scattering coefficient from zero to 10^4 m^{-1}. Thus, the approximate method gives sufficiently accurate results for practical purposes in cases where the contribution of radiation to the heat transfer within the material is substantial.

It is natural to postulate that the parameter connecting the rate of melting of the material with its optical properties is the reflectivity, since this parameter determines the amount of radiation absorbed by the

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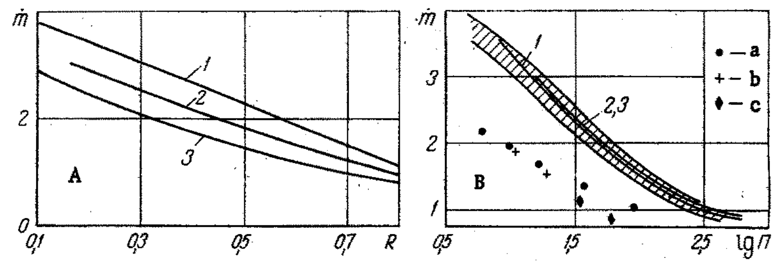

Fig. 1. Melting rate $\dot{m}$ as function of: A) reflectivity R (n_r = 1.5); B) parameter Π: 1) γ = 100; 2) 315; 3) 800 m^{-1}; a) α = 100, $\beta = 0\text{–}10^4$ m^{-1}, N < 0.5; b) $\alpha = 10^2\text{–}10^3$, β = 0, N < 0.5; c) $\alpha = 3.16\cdot10^3\text{–}10^4$, β = 0, N > 0.5 [2]. Π in $m^{-0.5}$; m in kg/m^2·sec.

material. Figure 1A shows a plot of the melting rate $\dot{m}$ against the reflectivity R for different values of the attenuation coefficient. The presented curves show that for R = 0.55 and γ = 100 m^{-1} the melting rate is greater than for R = 0.35 and γ = 800 m^{-1}, although the amount of radiation absorbed in the second case is 1.4 times that in the first case. This can be attributed to the increase in thickness of the melt film with increase in the radiation mean free path and, consequently, to the increase in the rate of ablation in the liquid phase [2, 3].

Figure 1B shows the results of the same calculations in relation to the parameter

$$\Pi = \sqrt{\gamma}/R_0^2(1+R_1),$$

where [3]

$$R_0 = (1-r)\, n_r^2\, \frac{1-\rho}{1-r\rho}\ ;\quad R_1 = \frac{1-\rho}{1+\rho}\ ;\quad \rho = \frac{\gamma-\alpha}{\gamma+\alpha},$$

and r_1 is the coefficient of reflection of radiation from the side surface of the body. The hatched strip on this figure contains the results of calculations for the above-indicated range of variation of the optical properties and for a value of the radiation–conduction parameter N not exceeding 0.5. Despite the very large range of variation of these properties the theoretical points lie in a fairly narrow band.

Similar results were obtained for other relative values of the radiative and convective heat fluxes, and also for different values of the shear forces. We also treated the results of calculations from [2], corresponding to the case where the radiative heat flux is 6.15 MW/m^2 and constitutes 75% of the total flux, in the form of a relation between the melting rate and the parameter Π. The value of the radiation–conduction parameter N in these calculations was 0.02–4.4. The greatest difference in the melting rate for the same values of the parameter Π and N < 0.5 does not exceed 9%. These results are also given in Fig. 1B.

Thus, numerous calculations show that the parameter Π can serve as an index of the effect of the optical properties of a material on its melting rate in the case where the radiative heat flux is more than one-third of the total heat flux. This applies to materials with refractive index up to 2.3, ratio of scattering coefficient to absorption from zero to 100, and radiation–conduction parameter from 0.005 to 0.5.

NOTATION

$\dot{m}$	is the mass melting rate;
N	is the radiation–conduction parameter;
n_r	is the refractive index;
R	is the reflectivity;
r	is the reflection coefficient on side surface of body;
ρ, R_0, R_1	are the coefficients depending on optical properties of material;
α	is the absorption coefficient;
β	is the scattering coefficient;
γ	is the attenuation coefficient;
λ	is the thermal conductivity;
Π	is the parameter;
σ	is the Stefan–Boltzmann constant;
T_w	is the surface temperature.

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CORRELATION OF THE TEMPERATURE COEFFICIENT OF LIQUID HEAT CONDUCTION AND THE SPEED OF SOUND

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Underlying the correlation under consideration are the known relationships between the temperature coefficients of the heat conduction, the density, and the speed of sound

$$\frac{d\lambda}{dT}\frac{1}{\lambda} = n\frac{d\rho}{dT}\frac{1}{\rho}, \tag{1}$$

$$\frac{d\rho}{dT}\frac{1}{\rho} = m\frac{dv}{dT}\frac{1}{v}, \tag{2}$$

where n and m are constants.

These relationships express the connection between the heat conduction and the density [1, 2] and the known Rao rule [3] in differential form.

It should be noted that (1) and (2) can be written in dimensionless form

$$\frac{d\left(\frac{\lambda}{\lambda_c}\right)}{d\left(\frac{T}{T_c}\right)}\frac{1}{\left(\frac{\lambda}{\lambda_c}\right)} \Bigg/ \frac{d\left(\frac{\rho}{\rho_c}\right)}{d\left(\frac{T}{T_c}\right)}\frac{1}{\left(\frac{\rho}{\rho_c}\right)} = f_1\left(\frac{T}{T_c}\right) = n, \tag{3}$$

$$\frac{d\left(\frac{\rho}{\rho_c}\right)}{d\left(\frac{T}{T_c}\right)}\frac{1}{\left(\frac{\rho}{\rho_c}\right)} \Bigg/ \frac{d\left(\frac{v}{v_c}\right)}{d\left(\frac{T}{T_c}\right)}\frac{1}{\left(\frac{v}{v_c}\right)} = f_2\left(\frac{T}{T_c}\right) = m. \tag{4}$$

In this form they express the similarity between the reduced temperature coefficients of the heat conduction and density on the one hand, and the temperature coefficients of the density and the speed of sound on the other.

It follows from (1) and (2) that

$$\frac{d\lambda}{dT}\frac{1}{\lambda} = nm\frac{dv}{dT}\frac{1}{v}. \tag{5}$$

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