SPECTRAL EXTINCTION COEFFICIENT OF VAPOR OF HEATPROOF MATERIAL DESTROYED BY A HIGH-TEMPERATURE FLUX OF AIR PLASMA

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The article presents the results of measurement of the spectral extinction coefficient of the destruction products of heatproof material in a stream of air plasma.

In connection with the practical interest in the problem of apparatuses entering the atmosphere of planets, questions connected with the interaction between hot emitting gas and disintegrating materials become highly topical. One of the chief tasks connected with this problem is the study of the optical properties of the multicomponent boundary layer; the effectiveness of reducing the heat flux from the compressed layer behind the shock wave to the apparatus depends on these properties. The investigation of the composition, temperature, and other radiation characteristics of the vapors of the boundary layer is therefore of practical importance. The present work examines these questions.

For modeling aerodynamic heating by the shock layer, a gasdynamic device [1, 2] was used. The device with high-frequency electrodeless heating of the gas satisfied the basic requirements that such a source must meet, viz., that a chemically pure high-temperature gas stream is obtained. The results of the present work were obtained in the optimum gasdynamic regime of the discharge. The region of the discharge is filled with hot gas, the discharge is eased away from the wall, and the process is stable and continues for an unlimited time. The principal parameters of the flow are: the heated gas is air, flow velocity $V \sim 30$ m $\cdot$ sec^{-1}, jet diameter $D \sim 0.04$ m, $P = 1$ kg $\cdot$ cm^{-2}.

To solve the problem of interaction between hot gas and the material, it is indispensable to know the parameters of the incoming high-temperature flow. All the measurements in the plasma were carried out in a cross section of the jet at a distance of ~0.01 m from the edge of the pipe.

The stationary method was used for measuring the heat flux to the intact calorimetric sensor and the flux distribution along the axis and the radius of the jet. Using sensors with different reflectance of the surface enabled us to divide the total heat flux $q \sim 0.4$ kW $\cdot$ cm^{-2} into a convective (~ 0.3 kW $\cdot$ cm^{-2}) and a radiational component (~ 0.1 kW $\cdot$ cm^{-2}). The given configuration is characterized by a considerable radiant component of the total heat flux. This has to do with the large emitting volume, where in the core of the discharge there are regions with $T \sim 10\text{-}12 \cdot 10^3$ °K. From the emission spectra of the air plasma, the temperature and the spectral absorption coefficient were determined. Georg and Yakushin [3] concluded on the basis of the coincidence of the measured vibrational, rotational, and electron temperatures N_2 (2+) and N_2^+(1-) and the excitation temperature of N and O atoms that in the working cross section of the plasma jet there is thermal equilibrium with a temperature of T = 8500°K and electron concentration $N_e \sim 3 \cdot 10^{15}$ cm^{-3}.

The temperature distribution along the radius indicates that near the axis there exists a region of constant temperature whose size is $d \sim 0.02$ m. The absorption coefficient of the plasma was calculated for an optically thin layer for the interval 0.3-0.9 μm on the basis of the measured radiation intensity and temperature. The spectral absorption coefficient of plasma changes within the limits 10^{-2}-10^{-4} rel. units; the principal contribution to absorption is provided by the molecular systems Na^+, NO, N_2 and the atoms N and O (Fig. 1, curve 2). The experimental values of the spectral absorption coefficient were compared with the calculated values obtained for an optically thin layer of air plasma in equilibrium; there is good agreement [3]. Thus the thermal effect of a plasma jet corresponds to convective and radiative heating modeling the spectral composition of the emission of a shock layer.

Models of heatproof material 0.08 m long had the shape of a plate 0.03 m thick with a cylindrical top with 0.015 m radius. The models were mounted on a traversing gear which was moved into the working section of the jet. The model was projected on a spectrograph slit in such a way that the emission of the

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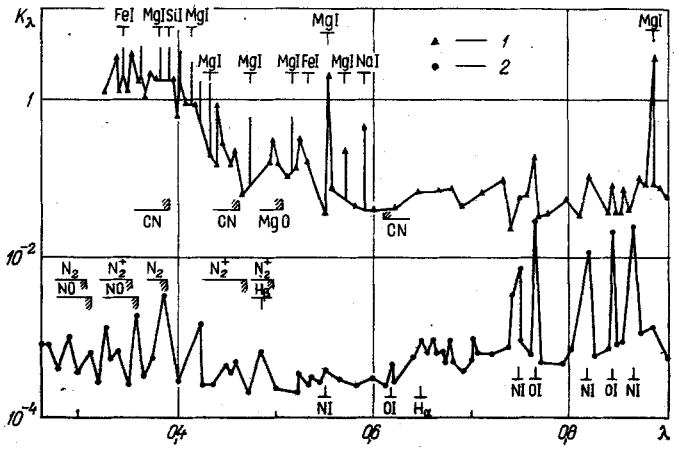

Fig. 1. Distribution of the spectral extinction coefficient of the destruction products (1) and of the absorption coefficient of plasma (2), K_λ, rel. units of wavelength λ, μm.

disintegrating model surface, of the boundary layer, and of the plasma was simultaneously recorded [2]; while the radiation intensity of the plasma was being measured, the model was removed. The spectra of the vapor emission and the plasma were photographed by a diffraction spectrograph DFS-13 with a dispersion of 2 Å·mm^{-1} in the range 0.2-0.9 μm. The spectra showed fairly distinct boundaries of the model surface–vapor–plasma and very intensive emission of the vapor exceeding the emission of the plasma.

The boundary layer was divided into several cross sections from the surface of the model to the plasma, perpendicularly to the line of observation whose orientation is parallel to the generatrix of the cylindrical top of the model in its plane of symmetry, in steps of $5 \cdot 10^{-4}$ m. In each cross section photometering was carried out across the spectral line. This made it possible to plot the temperature distribution across the boundary layer. Analysis of the obtained spectra enabled us to select the radical CN as the pyrometric molecule. By the intensity distribution in the rotational and vibrational structures of the CN bands, the corresponding rotational and vibrational temperatures were measured. The coincidence of these temperatures within the limits of accuracy of the experiment made it possible to ascribe to the boundary layer the gas temperature of the obtained profile. The temperature of the surface of the disintegrating material was determined by the brightness method and with the aid of a standard pyrometer ÉOP-66. In both cases the measured temperature was $T_w \sim 2800$°K. The obtained temperature profile was used for determining the composition of the multicomponent mixture from the measured absolute intensity of the emission of the lines. Pyrometric lines were selected which were free of interference by adjacent lines and reabsorption.

The electron concentration was determined from the broadening of the atom lines due to Stark's quadratic effect [4]. Analysis of the concentration distribution of the destruction products sheds light on the structure of the concentrational boundary layer. The destruction products concentrate in a layer near the wall that is relatively uniform in temperature, and next to this layer is the mixing zone which changes into a gas layer with components of the incoming flow. The temperature and concentration profiles indicate that the boundary layer is shifted, which is characteristic in cases of strong injection. There is practically no heat transfer by convection. The multicomponent high-temperature boundary layer containing destruction products in the gas phase and finely disperse particles is a scattering and absorbing medium, and it is therefore natural to characterize it by a physical parameter, viz., the extinction coefficient K_λ which depends on the temperature, pressure, composition, and wavelength.

For a mixture with constant composition, temperature, and pressure, being in a state of equilibrium, the extinction coefficient is determined from the transformed equation of transfer by the formula $K_\lambda = (1/l) \times \ln(1 - I_\lambda/B_\lambda)$, where I_λ, B_λ are, respectively, the measured intensity and radiation intensity of a black body; l is the length of the emitting layer. The extinction coefficient was determined in the boundary layer, at a distance $\sim 1 \cdot 10^{-3}$ m from the model wall, where the following conditions obtain: $T \sim 3700$°K, $P = 1$ kg·cm^{-2}, $l \sim 0.05$ m.

To determine the extinction coefficient, the spectral intensity of the vapor emission in the range 0.3-0.9 μm was measured. The intensity of the emission and consequently also the extinction were averaged over a spectral interval of 12 Å. It follows from a comparison of the nature of the emission of the vapor and of the

plasma of the incoming flow that the emission spectrum of the vapor has a more complex structure with distinct selectiveness and considerable intensity of the emission exceeding the emission of the air plasma. The most intensive emitters in the boundary layer are elements constituting a substantial part of the initial material. However, the principal components, viz., carbon and oxygen, are in a bound state and therefore are not among the important emitters.

In the range 0.6-0.7 μm the curve of spectral intensity of the vapor emission rises; this is possibly connected with the pressure of incandescent sublimating particles smaller than 20 μm in size (the extreme resolution of the objective) in the layer next to the wall, in the vicinity of the critical line. Experiments with recording of particles were carried out with the aid of filming and with spherical models which differed in their geometry from the models for spectral measurements. It was discovered that particles larger than 20 μm are blown from the surface of the model into the boundary layer in regions of the junction of geometric shapes where the velocity gradient is large.

Figure 1 shows the spectral distribution of the extinction coefficient of vapor (curve 1). The accuracy of measuring $K_\lambda \sim 30\%$. The figure also presents the distribution of the absorption coefficient of undistorted air plasma at T = 8500°K. Both coefficients are denoted K_λ and are given in relative units.

The increase in the extinction coefficient in the ultraviolet region is connected with the increase in optical density of the destruction products consisting of compounds of CN, having a large absorption cross section ($\sigma \sim 10^{-17}$ cm^2) and considerable concentration. A certain contribution to the extinction coefficient is provided by the transitions from the principal levels of the Mg and Al atoms. In this spectral region, lines with high excitation energy may affect the emission intensity, and consequently also K_λ. It can be seen from the graph that the components of air contribute little to the extinction coefficient of the vapors. The increase of the extinction coefficient in the continuous spectrum with decreasing wavelength is possibly connected with effects of scattering on the finely disperse particles smaller than 20 μm. A certain error in the extinction coefficient in this region is introduced by the edge effect, which distorts the homogeneity of the layer along the beam of observation, because in this spectral interval in particular, lines with considerable excitation potential are being excited. A comparison of the extinction coefficient of the vapors (Fig. 1, curve 1) with the absorption by the plasma (curve 2) leads to the conclusion that in the entire spectral interval the layer of destruction products is 2-4 orders of magnitude optically thicker than the layer of air plasma, regardless of its smaller geometric thickness; this is connected with the higher values of concentrations and absorption cross sections of the emitters. Therefore, when the total flux to the body is calculated, the emission by the destruction products of the boundary layer has to be taken into account.

NOTATION

T is the temperature;
P is the pressure;
V is the flow velocity;
D is the jet diameter;
q is the total heat flux;
N_e is the electron concentration;
λ is the wavelength;
K_λ is the absorption coefficient;
I_λ is the spectral intensity of radiation;
B_λ is the spectral intensity of black-body radiation;
l is the length of the emitting layer;
σ is the absorption cross section;
d is the size of the constant-temperature region;
T_w is the temperature of the disintegrating surface.

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