MODELING OF NATURAL IONOSPHERIC FLIGHT CONDITIONS

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In simulating conditions for flight of spacecraft in the upper layers of the atmosphere one must model the ionization, excitation, and dissociation of the flow [1], in addition to other parameters. Modeling of these parameters is important, in particular, in investigations of sensors intended for measuring flight parameters aborad a spacecraft, tests of structural materials, and determination of the aerodynamic characteristics of spacecraft. The studies described here employ multielectrode probes, a metastable particle detector, and catalytic sensors to investigate the ionized, dissociated, and excited components of high-speed free-molecular flow in a facility [2] which models flight conditions in the upper atmospheric layers. It is shown that the degrees of ionization and dissociation, and also the metastable particle concentration in the flow, correspond to the natural values of these parameters at altitudes $H = 120$–200 km.

§1. The investigations were conducted with a high-speed free-molecular nitrogen flow, isolated using a gasdynamic source from a high-temperature rarefied jet. The speed of the free-molecular flow was as high as $v = 3.5$–4 km/sec, the flux $j = nv = 2 \cdot 10^{17}$ $\text{cm}^{-2} \cdot \text{sec}^{-1}$, the speed ratio $S = 5$–10, the flow diameter $D \sim 0.1$ m [2], the stagnation temperature $T_0 = 5000$–6200°K, and the stagnation pressure was $p_0 = (2$–$5) \cdot 10^4$ N/m^2 [2]. The gas was heated by means of a high-frequency electrodeless discharge [3].

In the forechamber of the facility the gas temperature, rotational atmospheric and vibrational temperature coincided to within an error of 10% or better ($T_0 = T_V = T_r$), while the electron temperature was roughly a factor of 2 larger, $T_- = 2T_0$ [2, 3].

In the gas expansion the internal degrees of freedom are not able to relax. At vibrational and electron temperatures, the degrees of ionization and dissociation were stabilized, it is estimated, at a level corresponding to their values at the throat. For $T_0 = 5000$°K and $p_0 = (3$–$5) \cdot 10^4$ N/m^2 the flow values are $T_V = 4000$°K, the degree of dissociation $\alpha_0 = 1$–3%, and the degree of ionization $\alpha_+ \sim 10^{-2}\%$. The rotational temperature was stabilized at a consistently lower level $T_r = 400$°K [2].

For an increase of T_0 above 5000°K the degrees of ionization and dissociation rapidly increased. These conditions, which are of interest for modeling the natural conditions, were investigated in this work. We note that the high-speed free-molecular flow under investigation is weakly self-luminous, due, apparently, to decay of the metastable states $a'\Pi_g$ of the nitrogen molecule. There is also radiation from the discharge zone and recombination radiation from the jet adjacent to the nozzle exit. Therefore, in addition to investigating the ionized and dissociated flow components, the authors also measured radiation from metastable molecules and UV radiation. As is known, all these components are present in the upper atmosphere.

§2. The electron and ion flow components were studied by means of a modified multielectrode probe, which could measure the ionized component in the presence of an intense flux of neutral gas. Ordinary multielectrode probes [4] are constructed in the form of a chamber with apertures pointing toward the flow to be tested. In the intense flow investigated here a pressure of $p \sim 0.1$ N/m^2 is established in the chamber of this type of probe, and at this pressure normal operation of the probe breaks down. We used a probe in the form of a hollow truncated cone with a 50×50 μ grid collector. With this probe construction the perturbation introduced by the probe arc is reduced, and the gas flow through the probe is such that a low pressure, near the static pressure in the undisturbed stream, is set up within the probe.

From the results of measurements using multielectrode probes the energy of ions in the flow at $T_0 = 5000$–6200°K is $W_+ = 45$–70 eV; the ion temperature is $T_+ \sim 4000$°K; and the electron temperature is $T \sim 7$ eV. Figure 1 shows typical ion energy distribution functions [1) $T_0 = 5000$°K, 2) $T_0 = 5600$°K, 3) $T_0 = 6200$°K]. The speed ratio for the ions is $S_+ \sim 20$. The high ion energy values in the flow are due apparently to nonisothermal acceleration during discharge of a high-temperature jet to vacuum.

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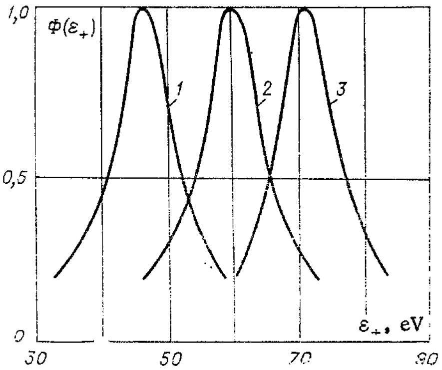

Fig. 1

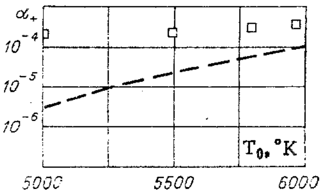

Fig. 2

From the ion flux intensities $j_+ = n_+v_+$, measured by means of multielectrode probes, and the ion mean velocities v_+, using the values of the intensity $j = nv$ and the velocity v of the neutral flux, we determined the degree of ionization in the flow:

$$\alpha_+ = n_+/n, \quad \beta_+ = j_+/j.$$

The measured ionization α_+ in the flow is compared in Fig. 2 with the equilibrium degree of ionization at temperature T_0 (dashed line). The ionization in the flow is 1-2 orders of magnitude greater than the equilibrium value corresponding to T_0. This is due to nonequilibrium of the discharge plasma. The electron temperature in the discharge is $T_- = 1$-2 eV. The values obtained for the degree of ionization in the flow are in good agreement with values in the forechamber, estimated from the skin layer in the discharge [3].

§3. The excited flow component was investigated by means of a detector which could record ions, metastable particles, and UV radiation. The detector is a type VÉU-1A electron multiplier, located in a mesh screen with a conical nose. In front of the entrance aperture of the detector screen two grids (mesh 50 × 50 μ) and interchangeable light filters (mounted on a supplementary traverse mechanism) were set up. One of the grids was at the potential of the probe body ($\varphi_1 = 0$), while the other had a potential which made it possible to analyze the ion component (the electron component is suppressed because of the large negative potential of the first VÉU dynode). With an analyzing grid potential of $\varphi_2 \approx 0$ and the light filter removed (conditions 1), the detector records ions, metastable particles, vibrationally excited molecules, and light quanta whose energy is greater than the exit function of the first VÉU dynode. When the analyzing grid has a potential greater than the energy of the flow ions $e\varphi_2 > W_+$, the detector records metastable particles, vibrationally excited molecules, and UV radiation.

Finally, with a light filter ahead of the detector, the detector records UV radiation which has passed through the filter. From the measured results under the above conditions one can evaluate the UV radiative flux and the concentrations of metastable, vibrationally excited, and ionized particles. The detector can also be used as a probe for energy analysis of the ions.

Figure 3 shows the detector current as a function of analyzing grid potential φ_2. On the characteristic section $\varphi_2 < 45$ V the probe records all the flow ions (the thermal ion background intensity is ~0.01 of the fast ion intensity), the metastable excited particles, and the UV radiation. For $\varphi_2 > 80$ V, all the ions are suppressed, and only metastable, excited particles, and UV radiation are recorded. From the results of these measurements we find that the relative content of metastable particles for $T_0 = 5000$-6200°K is 0.7-2%, and the UV flux is ~1-2% of the neutral particle intensity. The content of high-level vibrationally excited particles (with energy $W_v \geq 4$ eV) is estimated to be 1-2 orders of magnitude less.

§4. The dissociated component of the flux was investigated by means of sensitive heat flux sensors of compensated type [5] to measure the contribution to the thermal flux from atoms recombining on the catalytic surface, in comparison with the thermal flux to a noncatalytic surface. The catalytic sensor surface material was chosen to be silver (Ag) and the noncatalytic material was tungsten (W) [6]. The different catalytic nature of the materials manifests itself also, apparently, in interaction of ions and metastable particles with the surface, but their contribution to the thermal flux is small relative to that of the dissociated particles. The contribution of vibrationally excited particles is apparently larger.

Figure 4 shows the calculated and experimental specific heat flux as a function of the parameter $p_0\sqrt{T_0}$, where p_0 is the gas pressure in the forechamber and T_0 is the stagnation temperature. The points 1 correspond to the specific heat flux to a silver surface and the points 2 to a tungsten surface. Curve 3 corresponds

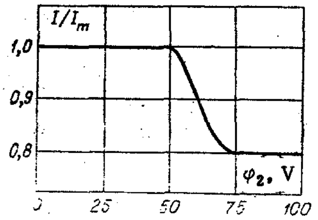

Fig. 3

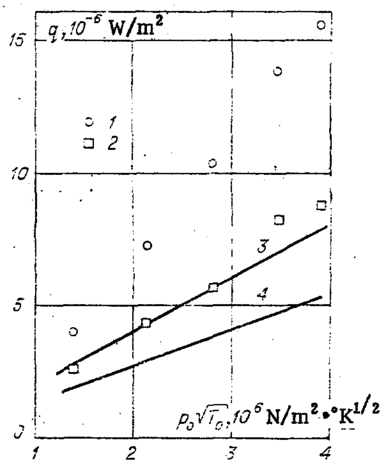

Fig. 4

to the theoretical specific heat flux to a noncatalytic surface, accounting for the contribution of ions, electrons, metastable and vibrationally excited particles, and also the light radiation. Curve 4 shows the heat flux to a noncatalytic surface, corresponding to translational energy of the flow $q = \rho v^3/2$ (with an energy accommodation coefficient $a = 1$), where ρ is the density and v is the flow velocity. The closeness of curve 3 to the points 2 is evidence that tungsten is practically noncatalytic, in contrast with silver (points 1). The degree of dissociation of the flow α_0, estimated from the results of these experiments, is $\alpha_0 = 10$–20% at a stagnation temperature $T_0 = 5500$°K.

Thus, the high-temperature free-molecular flow investigated is quite a good model of the natural conditions of interaction of a spacecraft with the earth's upper atmosphere. The flow velocity $v = 3.5$–4 km/sec, the intensity $j = 5 \cdot 10^{16}$–$2 \cdot 10^{17}\,\mathrm{cm}^{-2} \cdot \mathrm{sec}^{-1}$, the degree of ionization $\beta_+ = 10^{-2}$, the degree of dissociation $\alpha_0 = 10$–20%, and the relative concentration of excited particles is $\gamma \sim 1$–3%.

For comparison we present the corresponding values for a spacecraft at altitude $H = 120$–200 km. The flow velocity is $v = 8$ km/sec, the intensity is $j = 10^{16}$–$3 \cdot 10^{17}\,\mathrm{cm}^{-2} \cdot \mathrm{sec}^{-1}$, the degree of ionization is $\beta_+ = 10^{-5}$–10^{-3}, the degree of dissociation is $\alpha_0 = 10$–50%, and the relative concentration of excited particles is $\gamma \geq 10$–15% [7, 8]. These data show that the laboratory conditions agree quite well with the natural conditions.

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