A practical problem proposed by P. I. Akimov was considered, involving calculation of an electron gun in an electron-optical system, the geometry of which is shown in Fig. 3. The pressure of the residual gas, assumed to consist of nitrogen molecules, was p = 0.667 Pa, with ionization section assumed constant for all energies ($\sigma_i = 3 \cdot 10^{-18}$ cm^2). The solid line of Fig. 3 shows the behavior of electron trajectories, while the dashed line is an example of ion trajectory behavior.

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VIBRATIONAL RELAXATION OF CO_2 MOLECULES DURING INJECTION INTO THE IONOSPHERE

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The problem of the influence of spacecraft flights on the state of the atmosphere is raised in connection with the active conquest of space. Spacecraft engines throw a large amount of H_2O, H_2, and CO_2 molecules into the atmosphere. The injected gas, in expanding, occupies volumes in the atmosphere with linear sizes of tens and even hundreds of kilometers. In this case the concentration of the ejected molecules remains comparable with the concentration of the atmospheric components. From this point of view, the injection of exhaust gases can make an appreciable contribution to the local heat balance of the atmosphere. The problem of the vibrational relaxation of water molecules behind a shock wave was discussed in [1] in connection with the above-indicated problem. The problem of the vibrational relaxation of CO_2 during mixing with the atmospheric gas is solved in the present work.

In the temperature range of 2000-3000°K the vibrational relaxation of CO_2 in collisions with molecules takes place more slowly than that of H_2O, while the rates of excitation of the vibrational degrees of freedom of CO_2 by electrons are considerably higher (by about 10^3). In the F region of the ionosphere the degree of ionization of the atmospheric gas reaches 10^{-3}, and hence electrons can play a definite role in the excitation of CO_2 vibrational levels, which in turn affects the thermal radiation.

Since the excitation of molecular gases by electrons is a natural phenomenon observed in the upper layers of the atmosphere, many papers have been devoted to this problem. A survey of papers on the rates of electron cooling in the ionosphere is made in [2], while [3] is devoted to the infrared emission of the undisturbed upper atmosphere with allowance for the excitation of CO_2 vibrational levels by electrons and the influence on the intensity of

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infrared emission of the electric fields existing in the ionosphere. The problem of the influence of electrons and electric fields on vibrational energy exchange during the mixing of the atmospheric and injected gases is raised in the present paper. Since a considerable decrease in the electron density is observed upon the injection of H_2O and H_2 molecules into the ionosphere [4], this effect is also taken into account.

The model problem is stated as follows. It is assumed that the atmospheric and injected gases are mixed instantaneously with equal flow rates and are heated by deceleration due to the velocity difference. A discontinuity of the gasdynamic parameters occurs in this case, analogous to the passage of a shock wave through the mixture. We consider the case in which the mixture is heated to temperature of ∿2000°K by such mixing and is compressed by a factor of two to three. In the calculations, the results of which are presented below, the injected gas consists of equal amounts of CO, H_2, and H_2O with a 4% admixture of CO_2. The composition and gasdynamic parameters of the atmospheric gas are taken from CIRA-72.

The system of equations of gasdynamics describing the shock wave (here and below, by the shock wave we mean the discontinuity indicated above), equations for the populations of the N_2, CO, and CO_2 vibrational levels, and equations describing the variation of the electron density is solved numerically.

The system of gasdynamic equations is written in the usual notation in the form

$$\rho u = \rho_1 u_1 + \rho_2 u_2 = 2\rho_1 u_1; \tag{1}$$

$$\rho u^2 + nkT = \rho_1 u_1^2 + \rho_2 u_2^2 + n_1 kT_1 + n_2 kT_2; \tag{2}$$

$$\frac{\rho u^3}{2} + nuc_{pf}k\left[T - (\Delta T)^{H_2O}\right] + nu\left(c^{CO}\mathscr{E}^{CO} + c^{CO_2}\mathscr{E}^{CO_2}\right) = \frac{\rho_1 u_1^3}{2} + \frac{\rho_2 u_2^3}{2} + n_1 u_1 c_{p1} kT_1 + n_2 u_2 c_{p2} kT_2 - Q, \tag{3}$$

where the index 1 refers to the atmospheric gas and 2 to the injected gas; c_{pf} is the heat capacity, taken with allowance for the fact that the CO and CO_2 molecules are not vibrationally excited; c^{CO} and c^{CO_2} are the CO and CO_2 concentrations; Q is the integral emission from the mixture.

The vibrational kinetics of H_2O was calculated separately. Assuming that the H_2O vibrational levels do not interact with the vibrational levels of the other components, to simplify the calculation we can introduce into the problem the temperature decrease $(\Delta T)^{H_2O}$ due to the emission of water. Therefore, a calculation was made by the program used in [1] for the conditions behind the shock wave and the composition of the mixture that we are considering [the temperature decrease was introduced into the system (1)-(3) at each step of the calculation].

The system of equations for the populations of the CO, CO_2, and N_2 vibrational levels,

$$\frac{d\alpha_i}{dt} = \sum_K \left\{ n^K \left[\sum_j W_{ji}^K \alpha_j - \left(\sum_j W_{ij}^K \right) \alpha_i \right] \right\} - \frac{\alpha_i}{\tau_i},$$

where i and j are the numbers of the vibrational levels, W_{ij}^K is the rate constant of the transition between the levels, α_i is the population of the i-th level, τ_i is the lifetime of the i-th level, and K is the partner in the collision, which can be N_2, CO_2, CO, O, H_2, H_2O, or e^-, was solved jointly with the gasdynamic equations. Because of the low temperatures, we took into account the first vibrational levels of N_2 and CO and of the ν_3 mode of CO_2 and the four lowest vibrational levels of the ν_2 mode of CO_2 in the problem.

The decrease in electron density is accomplished in the processes [4]

$$H_2 + O^+ \xrightarrow{k_1} OH^+ + H, \quad k_1 = 2\cdot 10^{-9}\ \text{cm}^3/\text{sec}; \tag{4}$$

$$H_2O + O^+ \xrightarrow{k_2} H_2O^+ + O, \quad k_2 = 2{,}4\cdot 10^{-9}\ \text{cm}^3/\text{sec}; \tag{5}$$

$$OH^+ + e^- \xrightarrow{k_3} O + H, \quad k_3 = 10^{-7}\ \text{cm}^3/\text{sec}; \tag{6}$$

$$H_2O^+ + e^- \xrightarrow{k_4} H_2 + O, \quad k_4 = 3\cdot 10^{-7}\ \text{cm}^3/\text{sec}, \tag{7}$$

The rates of these reactions exceed by an order of magnitude the rate of the main recombination process balancing the photoionization process in the undisturbed ionosphere:

$$O^+ + N_2 \rightarrow NO^+ + N,\ NO^+ + e^- \rightarrow N + O.$$

The equations describing the processes (4)-(7) were also introduced into the problem.

The question arises of the evolution of the electron energy due to the contribution to the excitation of CO_2 vibrations. The equation for the electron temperature was solved jointly with the above-described system of equations. It was first written in the form proposed in [3] for the undisturbed ionosphere, so as to obtain the electron temperature at which they are mixed with the injected gas.

In writing the equation for the electron temperature in the nonsteady case with mixing of the injected and atmospheric gases, we must allow for the rate of electron cooling on all the components of the mixture. In the region of electron temperatures recorded in the ionosphere, we can assume that the vibrational excitation of CO, H_2, and H_2O by electrons is considerably less than the excitation of rotational degrees of freedom [5-7]. For degrees of ionization of $<10^{-3}$ the translational energy exchange between electrons and neutral particles becomes efficient [8]. Electron cooling in the vibrational excitation of CO_2 is also an important process [2].

The rates of electron cooling in the excitation of rotational degrees of freedom of H_2 and CO_2 molecules and of vibrational degrees of CO_2 were calculated from the equations of [2], where the values $B = 60.81$ cm^{-1} and $q = 0.484$ were taken for H_2. These equations are not valid for molecules possessing a dipole moment. Therefore, the cross section for the excitation of rotational degrees of freedom of the CO molecule by slow electrons was taken from [6], the experimental data of which can be described approximately by the equation

$$\sigma_{CO}^{R} = 8{,}4\cdot 10^{-15} T_e^{-1} \ln (T_e/18{,}3).$$

The same relation was used in [6] for the analysis of H_2O, where satisfactory agreement with the available experimental results was obtained.

In allowing for elastic collisions, we adopted the usual gas-kinetic cross sections. Thus, to the terms describing electron cooling in the equation from [3] we added the following:

$$\left(\frac{dT_e}{dt}\right)_{H_2O} = \left\{1{,}42\cdot 10^{-16}\left(1 + \frac{961}{T}\right) T_e^{1/2} + 5{,}2\cdot 10^{-9} \ln (T_e/18{,}3)\, T_e^{-1/2}\right\} n^{H_2O} (T_e - T),$$

$$\left(\frac{dT_e}{dt}\right)_{H_2} = \left\{1.22\cdot 10^{-15}\left(1 + \frac{234}{T}\right) T_e^{1/2} + 1.66\cdot 10^{-9} T_e^{-1/2}\right\} n^{H_2} (T_e - T),$$

$$\left(\frac{dT_e}{dt}\right)_{CO} = \left\{1.44\cdot 10^{-16}\left(1 + \frac{101}{T}\right) T_e^{1/2} + 5{,}2\cdot 10^{-9} \ln (T_e/18{,}3)\, T_e^{-1/2}\right\} n^{CO} (T_e - T),$$

$$\left(\frac{dT_e}{dt}\right)_{CO_2} = \left\{4{,}5\cdot 10^{-10} T_e^{-1/2} + 6{,}2\cdot 10^{-10}\left(1 + 2{,}5\cdot 10^{-3} (T_e - T)\right)\right\} n^{CO_2} (T_e - T).$$

The final equation for the electron temperature in the nonsteady case has the form

$$\frac{dT_e}{dt} = \frac{2\cdot 10^{15}}{\nu_{ei} + \nu_{en}} \left[E_{\parallel}^2 + E_{\perp}^2 \frac{(\nu_{ei} + \nu_{en})^2}{(\nu_{ei} + \nu_{en})^2 + \omega_e^2}\right] + \frac{7{,}73\cdot 10^3}{N_e} \overline{E} q^{\text{ph. ion}} - \left(\frac{dT_e}{dt}\right)_i$$

$$- \left(\frac{dT_e}{dt}\right)_O - \left(\frac{dT_e}{dt}\right)_{N_2} - \left(\frac{dT_e}{dt}\right)_{H_2O} - \left(\frac{dT_e}{dt}\right)_{H_2} - \left(\frac{dT_e}{dt}\right)_{CO} - \left(\frac{dT_e}{dt}\right)_{CO_2}.$$

Ionization by precipitating particles is not important for the ionospheric regions under consideration. Because of the low densities, the absorption of radiation is minor, so that we can take $W_z^{\text{ph.ion}} = W_{\infty}^{\text{ph.ion}}$ [9].

This system of equations was solved for different densities of atmospheric gas characterizing the F region of the ionosphere. The electron density was taken from [10-12], while the vibrational temperature of nitrogen for the corresponding conditions was taken from [3, 13].

The calculated results presented below were obtained for $n_1 = 8\cdot 10^8$ cm^{-3}, $T_1 = 900$°K and a degree of ionization of 10^{-3} (case 1); $n_1 = 8\cdot 10^9$ cm^{-3}, $T_1 = 700$°K, and a degree of ionization of 10^{-4} (case 2); $n_1 = 5\cdot 10^{10}$ cm^{-3} and $T_1 = 600$°K (case 3). In the third case the calculations were made for different degrees of ionization, $7\cdot 10^{-6}$ in daytime and $2\cdot 10^{-6}$ at night [12]. According to certain data [11], the degree of ionization in case 3 falls to $2\cdot 10^{-8}$ under night conditions. In cases 1 and 2 the electron density remains high around the clock because the plasma fluxes are directed downward from the plasmasphere into the ionosphere at night [9].

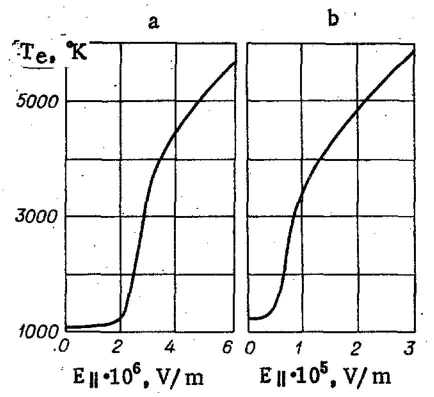

Fig. 1

The solution of the equation for the electron temperature in the undisturbed ionosphere as a function of the parallel component of the electric field for the daytime mid-latitude ionosphere during moderate solar activity is presented in Fig. 1 for cases 1 (a) and 2 (b). The term containing the perpendicular component of the electric field does not contribute to the electron temperature for reasonable values up to 0.1 V/m [14], since the gyrofrequency exceeds the values of ν_{ei} and ν_{en} by several orders of magnitude under our condition (H $\approx$ 0.45 G).

The behavior of the electron temperature as a function of distance, normalized to the mean free path l of the molecules in the mixture, is presented in Fig. 2 for cases 2 and 3 (lines 1-3 correspond to $E_{\parallel} = 3 \cdot 10^{-5}$, $6 \cdot 10^{-6}$ V/m, and $E_{\parallel} = 0$). It is seen that after the mixing of the atmospheric and injected gases, the electron temperature relaxes rapidly (over several l) to a certain value characterizing the equilibrium between the different mechanisms of electron heating and cooling. This characteristic temperature is only a few tens of degrees below the temperature of the mixture. Thus, the electric field will influence the vibrational relaxation only in a narrow section at the boundary of the cloud of injected gas, into which "fresh" electrons penetrate from the ionosphere. Since the electric field in the ionosphere varies rapidly with time (over intervals of $\sim$1 min), the calculation was made for the case when the electric field starts to grow to $E_{\parallel} \approx 10^{-3}$ V/m at the time of mixing of the gases (such fields can develop during geomagnetic storms). The calculation showed, however, that even such a field is unable to heat the electrons by any amount over the times under consideration, owing to the compression of the gas and the increase in energy losses by the electrons to the excitation of internal degrees of freedom of the components of the injected gas. Thus, during the mixing of the atmospheric and injected gases, the electron temperature remains high enough for the electrons to make a significant contribution to the vibrational excitation of CO_2 molecules.

In Fig. 3 we present calculations of the population of the first vibrational level of the ν_3 mode of CO_2 as a function of the distance behind the shock wave for case 1 (lines 1 and 2 correspond to $E_{\parallel} = 6 \cdot 10^{-6}$ V/m and $E_{\parallel} = 0$). The temperature T_v of the vibrational degrees of freedom of CO_2 is very low for these conditions: $T_v \approx 170$°K without allowance for e^- (at night). The electrons raise T_v to 210°K. The population of the ν_3 mode of CO_2 before mixing with the atmospheric gas was assumed to be zero, since the main channel of ν_3 excitation consists of collisions with electrons and atmospheric nitrogen. The next channel in significance, exchange of vibrational energy with the ν_2 mode of CO_2, yields a population an

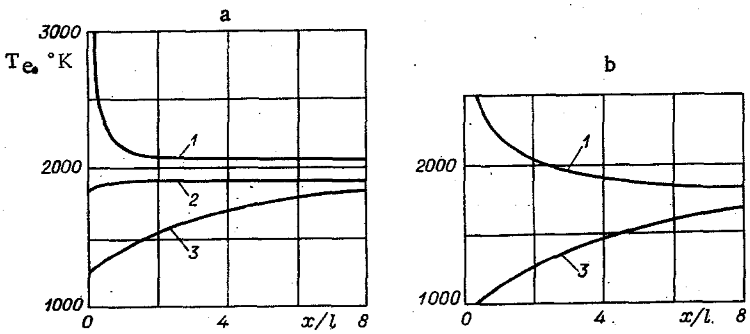

Fig. 2

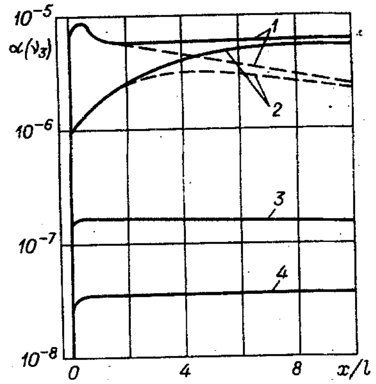

Fig. 3

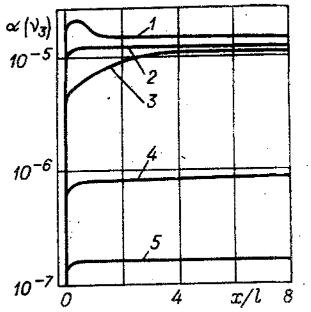

Fig. 4

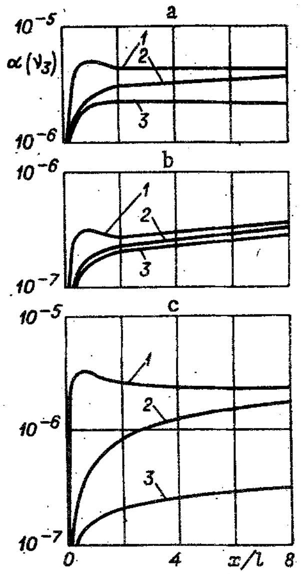

Fig. 5

order of magnitude lower than those presented in Figs. 3-5 at the temperatures under consideration. In Fig. 3 it is shown that under these conditions the electrons make the main contribution to the excitation of the ν_3 mode of CO_2, and we present calculations without allowance for electrons for the daytime and night populations of atmospheric nitrogen (lines 3 and 4) and with electrons with and without an electric field. As already mentioned, an influence of the field on the ν_3 population is observed only at the boundary of the cloud of injected gas, where the electrons arrive from the undisturbed region of the ionosphere. The populations of the ν_3 mode of CO_2 with allowance for the effect of a decrease in the electron density are marked by dashed lines. Under these conditions the decrease in the ν_3 population over a distance of $10l$ is $\sim 30\%$. Subsequently, this effect should be moderated by the diffusion of the cloud into the surrounding gas. As was shown in [4], during spacecraft flights the electron density falls by a factor of about three and reaches a minimum at times exceeding by an order of magnitude the times considered here, which comprise several seconds from the time of injection of the gas. In cases 2 and 3 the process of "eating away" of the electrons is insignificant over the times under consideration.

The behavior of the ν_3 mode of CO_2 for case 2 is presented in Fig. 4 [lines 1-3 correspond to $E_{\|} = 3 \cdot 10^{-5}$ and $6 \cdot 10^{-6}$ V/m and $E_{\|} = 0$, line 4 is without e^- (daytime), and line 5 is without e^- (night)]. It is seen that under these conditions electrons also play the main role in the process of vibrational excitation of CO_2.

The population of the ν_3 mode of CO_2 for case 3 is shown in Fig. 5 (lines 1 and 2 correspond to $E_{\|} = 5 \cdot 10^{-5}$ V/m and $E_{\|} = 0$ and line 3 is without e^-); Fig. 5a shows the daytime ionosphere with a degree of ionization of $7 \cdot 10^{-6}$. The process of resonance exchange with atmospheric nitrogen and collisions with electrons make equal contributions to the excitation of the ν_3 mode of CO_2. The picture may be different for the night ionosphere. According to [11], where it is indicated that the degree of ionization of the ionospheric gas falls to $2 \cdot 10^{-8}$ under such conditions, the contribution of electrons and atmospheric nitrogen to the process under consideration is small, while the ν_3 mode of CO_2 is populated by V–V exchange with the ν_2 mode (Fig. 5b). A degree of ionization of $2 \cdot 10^{-6}$ for the same conditions is indicated in [12]. It is characteristic that electrons determine the population of the ν_3 mode of CO_2 in this case (Fig. 5c).

As for the population of the ν_2 mode of CO_2, it does not experience such well-expressed influence of the enumerated processes, since the ν_2 mode, in contrast to ν_3, is well excited both by electrons and by collisions with molecules.

The gasdynamic parameters of the mixture (except for T_e) vary little over the distances behind the shock wave under consideration. The weak outflow of energy from the mixture due to the emission of CO_2 and CO, the populations of the vibrational levels of which are low, does not influence the gasdynamics of the problem. Emission by water over the times under consideration cools the mixture by no more than 10°K. In conclusion, we note that the degree of ionization characteristic for the mid-latitude daytime ionosphere was taken in the calculations for cases 1 and 2. Seasonal and diurnal variations may lead to a severalfold decrease in the electron density [15]. During high solar activity the electron density may be higher than that used in the present work. However, these variations do not affect the qualitative picture of the calculations made.

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