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Nonequilibrium ionization in carbon dioxide hypersonic flows about blunted bodies

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NONEQUILIBRIUM ionization in the shock layer about sphericaly-blunted cones is considered for flight velocity 4-7 km/s and ambient density 10^{-8}–10^{-5} g/cm^3. Nitrogen and sodium impurities effects on electron concentration is investigated.

Rozważa się przypadek nierównowagowej jonizacji w warstwie uderzeniowej opływającej sferycznie zatępiony profil stożkowy przy prędkościach 4-7 km/s i gęstości otoczenia 10^{-8}–10^{-5} g/cm^3. Uwzględniono wpływ domieszek azotu i sodu na koncentrację elektronów.

Рассматривается неравновесная ионизация в ударном слое при обтекании сферически затупленных конусов со скоростью 4—7 км/сек при плотности набегающего потока $10^{-8}-10^{-5}$ г/см^3. Исследуется влияние примесей азота и натрия на концентрацию электронов.

1.

HYPERSONIC viscous blunt body flows of nonequilibrium multicomponent gas mixtures have been investigated on the base of Navier-Stokes equations in our previous papers [1-3]. Numerical method and calculation results for axisymmetric carbon dioxide flows past spherically-blunted cones have been presented. Chemical reactions between neutral species and vibrational relaxation of CO_2 molecules have been taken into account.

Here nonequilibrium shock layer ionization is numerically investigated. For the flight conditions, the considered ionization effect on the flow field parameters is negligible. Thus gas dynamic functions and neutral species distributions obtained in [1-3] are used. It is supposed that the mixture quasi-neutrality is violated only within the sheath region near the body surface. Ambipolar diffusion is described by means of a constant effective Schmidt number. For the flight velocities less than 7 km/s shock layer ionization occurs mainly as a result of collisions of heavy particles. Because of this fact and the high efficiency of energy exchange between electrons and molecules, it is possible to assume the electron temperature to be equal to the heavy particles translational temperature [4]. This assumption is in agreement with experimental data [5].

Under the assumptions mentioned above, the set of continuity equations for ions have to be solved to obtain electron concentration. The continuity equation for i-th ion species is

$$(1.1)\quad -\frac{\partial}{\partial n}\left(\frac{\mu}{Sc}\frac{\partial C_i}{\partial n}\right)+\left[\varrho v-\frac{\mu}{Sc}\left(\frac{\varkappa}{1+\varkappa n}+\frac{\cos\theta}{r+n\cos\theta}\right)\right]\frac{\partial C_i}{\partial n}+\frac{\varrho u}{1+\varkappa n}\frac{\partial C_i}{\partial s}=\omega_i.$$

It contains only a normal component of the mass diffusion flux according to strong variation of the species concentrations across the shock layer. Here s, n are the distances along and normal to the body surface, C is mass fraction, ϱ and μ are the density and viscosity of the mixture, Sc is the Schmidt number, u, v are the velocity vector components in the s, n-directions, $\varkappa$ is the curvature of generatrix of the body surface, θ is the angle between generatrix and free stream direction, r is the distance from the symmetry axis to the body surface, ω is the mass chemical production rate.

The boundary conditions for the parabolic set of equations (1.1) are formulated as follows. Symmetry relations are used at the stagnation line. Ion concentrations behind the detached shock wave are determined by modified Rankine – Hugoniot relations. Body surface is supposed to be insulated and absolutely catalytic as regards ions recombination. Its temperature is assumed to be equal to 1100°K. For the case of a collisionless charged layer near the body surface, the wall boundary condition is written according to [6, 7]

$$\frac{\mu}{Sc}\frac{\partial C_i}{\partial n} - 0.8\varrho\sqrt{\frac{RT_w}{m_i}}C_i = 0, \tag{1.2}$$

where R is the universal gas constant, m is the molecular weight. When a mean free path of molecules near the body surface is less than Debye length, the violation of quasi-neutrality is ignored and an approximate boundary condition

$$C_i = 0 \tag{1.3}$$

is used at the body surface.

While investigating the nitrogen impurity effect on the shock layer ionization, the continuity equations for neutral species N_2, NO, N are solved along with continuity equations for ions. The effective Schmidt number for neutral components is assumed to be equal to 0.5.

Ablation of some body surface materials results in the appearance of sodium vapour in the shock layer. To account for its effect the continuity equation for element Na concentration is solved. The wall boundary condition for this equation represents a balance between the diffusion flux of the element Na to the body surface and its production rate due to ablation.

Continuity equations are integrated numerically by means of an implicit finite-difference scheme of first-order accuracy on s and second-order accuracy on n-coordinates. At each step on s the set of difference equations is solved with the aid of the vector elimination method using the Newtonian iterative procedure.

2.

In the preliminary calculations above 40 reactions between neutral and charged particles were taken into account including ionization by electron and heavy particles impacts, associative ionization and charge exchange. Numerical analysis showed that the following reactions between the charged particles provide a main contribution (above 90%) to the electron density in the shock layer:

(1) $N+0 \rightleftarrows NO^+ + e$, (6) $CO+CO^+ \rightleftarrows C^+ + CO_2$,

(2) $C+0 \rightleftarrows CO^+ + e$, (7) $Na+M \rightleftarrows Na^+ + e + M$,

(3) $O+O \rightleftarrows O_2+e$, (8) $O_2+Na^+ \rightleftarrows O_2^+ + Na$,
(4) $CO+NO^+ \rightleftarrows CO^+ + NO$, (9) $NO+Na^+ \rightleftarrows NO^+ + Na$,
(5) $CO+O^+ \rightleftarrows CO^+ + O$, (10 $CO+Na^+ \rightleftarrows CO^+ + Na$.

Here M is any particle of mixture. The rate constants presented in [8–11] are used. For the case of pure carbon dioxide free stream the correspondent reactions are excluded from the ionization analysis. Chemical reactions between neutral mixture components and their rate constants are presented in [8].

3.

Some calculation results are plotted in Figs. 1–5. Distances along and normal to the body surface are referred to the body nose radius *a*. Profiles of number density of electrons N_e (1/cm^3) at the stagnation line for pure carbon dioxide free stream are presented in Fig. 1 ($V_\infty = 5.5$ km/s, $\varrho_\infty = 0.21 \times 10^{-6}$ g/cm^3, $a = 0.2$ m). These results demonstrate the electron density dependence on some assumptions accepted while formulating the problem. Curves *1* and *2* correspond to absolutely catalytic and noncatalytic body surface as regards dissociation–recombination reactions. Solid and dash lines *2* are the profiles of electron number density calculated with ambipolar Schmidt numbers Sc = 0.25 and Sc = 0.5. It is seen that the N_e profile is only slightly influenced by the variation of the catalytic properties of the body surface and ambipolar Schmidt number value. All other calculations were performed for the case of an absolutely catalytic wall with an ambipolar Schmidt number value Sc = 0.25. The profiles of mass fractions of ions for this variant are plotted in Fig. 2.

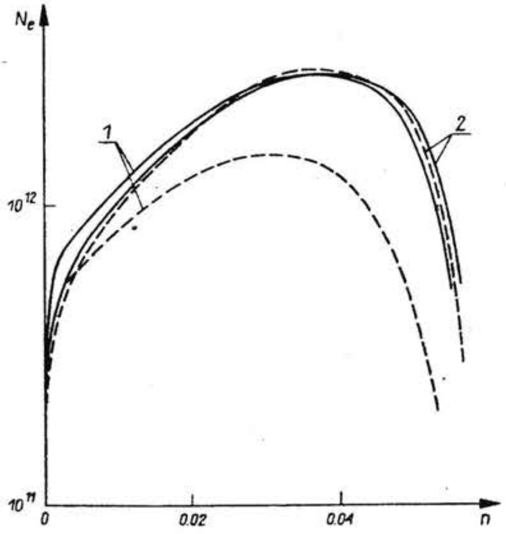

FIG. 1.

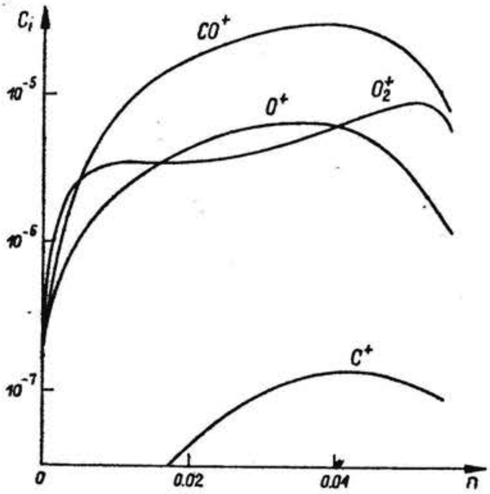

FIG. 2.

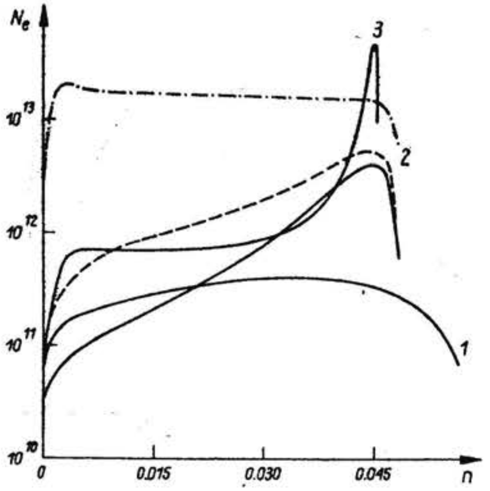

FIG. 3.

To estimate the effect of thermal nonequilibria between electrons and heavy particles, the calculations were performed with electron temperature equal to the vibrational temperature of CO_2 molecules A negligible variation of the electron density profile was found as a result of such deviation of the electron temperature from the translational temperature of the heavy particles.

An N_e profile obtained under the assumption of vibrational equilibria for all molecules is shown with the dash line *1*. We can see a significant carbon dioxide vibrational relaxation influence on the electron concentration.

Profiles of electron number density at the stagnation line for various ambient density values are presented in Fig. 3 ($V_\infty = 5.5$ km/s, $a = 1$ m). Curves *1*, *2* and *3* correspond

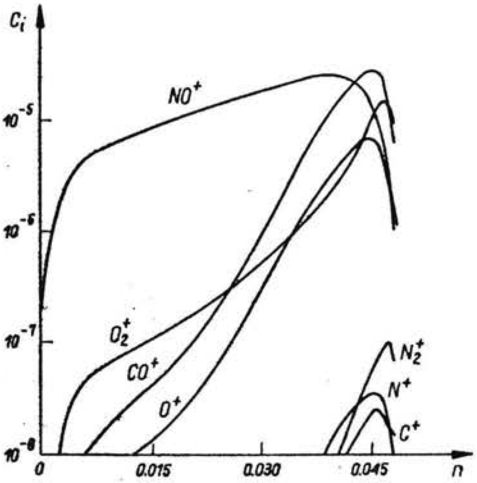

FIG. 4.

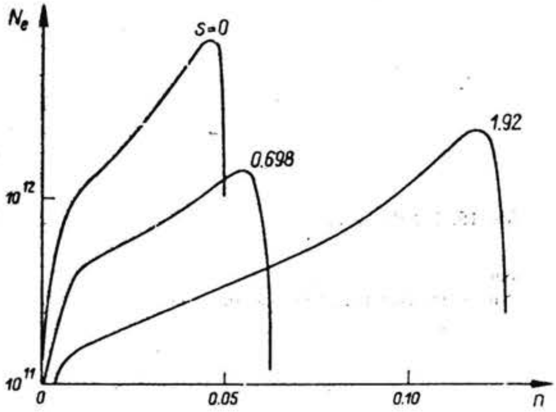

FIG. 5.

to $\varrho_\infty = 0.3\times10^{-7}, 0.3\times10^{-6}, 0.3\times10^{-5}$ g/cm^3 and illustrate the transition from a frozen to equilibrium shock layer ionization.

Calculation results for pure carbon dioxide free stream are shown in Fig. 3 by solid lines. The dash line *2* corresponds to the initial mixture composition 99% CO_2+1% N_2 (by mass). Profiles of mass fractions of ions for this variant are plotted in Fig. 4.

Electron density may be significantly increased by the sodium impurity originating from the ablation of the body surface material. According to the data presented in [8] for Martian atmosphere entry, the rate of element Na production at the body surface was assumed to be equal to 0.5×10^{-4} g/cm^2 s. Profile of the number density of electrons, calculated with the sodium impurity effect taken into account for the initial mixture composition 99% CO_2+1% N_2, are shown in Fig. 3 by the dotted curve *2*.

For a collisionless regime of the charged layer ($\varrho_\infty \approx 10^{-7}$ g/cm^3) it was found that the utilization of the wall boundary condition (1.3) instead of Eq. (1.2) results in a notable variation of the N_e value only in two or three mesh points near the body surface. The validity of the approximate relation (1.3) for both collisional and collisionless charged layer regimes was established earlier by KNIGHT [12] and NISHIDA [13] for air and argon weakly-ionized shock layers.

Variation of the electron number density in the shock layer along the body surface is illustrated by the results presented in Fig. 5 for the spherically-blunted cone with a half-angle 60° and a nose radius $a = 1$ m at $V_\infty = 5.5$ km/s, $\varrho_\infty = 0.3\times10^{-6}$ g/cm^3. Here initial mixture composition is assumed to be 98% CO_2 + 2% N_2. Non-monotonous variation of N_e maximum along the shock layer is observed.

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