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EFFECT OF THE BLUNT-END RADIUS OF A CONE MOVING IN AIR AT HYPERSONIC VELOCITY ON THE IONIZATION OF THE REGION DISTURBED BY IT

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A procedure is expounded in [1] for a global calculation of the region disturbed by an axisymmetric body moving at hypersonic velocity at zero angle of attack with Reynolds numbers $\mathrm{Re}_\infty \geqslant 3\cdot 10^3$ (the number Re_∞ is constructed from parameters in the oncoming flow and the blunt-end radius). The computational procedure is based on taking approximate account of all effects of fundamental importance to the formation of the flow field, namely: nonequilibrium physicochemical processes in the entire disturbed region, transport processes near the surface of the body and in the distant wake, viscous drag of the gas, and a decrease (in the case of a cold wall) of the total enthalpy in the viscous subregion of the near wake. The procedure is justified both by considerations of a physical nature and by experimental and theoretical data existing in the literature [1-4].

The procedure for calculation of the wake behind a body in [1] includes a calculation of the viscous subregion of the near wake and assumes the use as initial data of the distributions of the parameters of a mixture of gases near the cutoff of the body obtained with the transport processes near the lateral surface of the body taken into account (and also the inflow of foreign gases from the surface of the body if this occurs). As a result the procedure of [1], in contrast to other procedures, is applicable to the calculation of the wakes behind bodies with any blunt-end radius.

The characteristic peculiarities of the effect of the blunt-end radius of a moving body on the ionization of the flow field are investigated in this paper on the basis of an analysis of the computational data obtained with the use of the procedure of [1]. A discussion is conducted with the example of the motion of spherically blunt cones with apex half-angle 10° and length 1.5 m in the atmosphere of the Earth at an altitude of 50 km with velocity 7.4 km/sec. It is assumed that the surface of the cones is ideally catalytic and its temperature is 1000°K. Inflow through the surface and disintegration of the surface of the body are absent.

The system of physicochemical processes used in the calculations is given in [1]. An effective sticking process was additionally taken into account according to the data of [5] in connection with the calculation of the wake.

Let us first dwell on the question of the effect of transport processes on the formation of the plasma parameters near the lateral surface of the body. Computational data on the distribution of the electron density and temperature near the cutoff of the cones for the cases $r_0 = 15$ and 60 cm, respectively (r_0 is the blunt-end radius), are given in Figs. 1 and 2. The dashed curves denote a calculation without transport processes taken into account (according to the procedure of [4]), and the solid curves denote a calculation with the boundary layer taken into account (according to the procedure of [2]). The electron density axis n is shown at the top, and the temperature axis t in units of 1000°K is at the bottom. The coordinate normal to the contour of the body is plotted along the ordinate.

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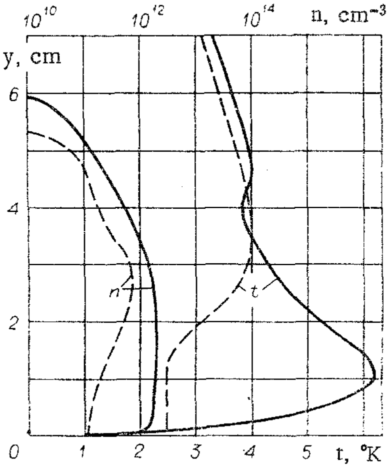

Fig. 1

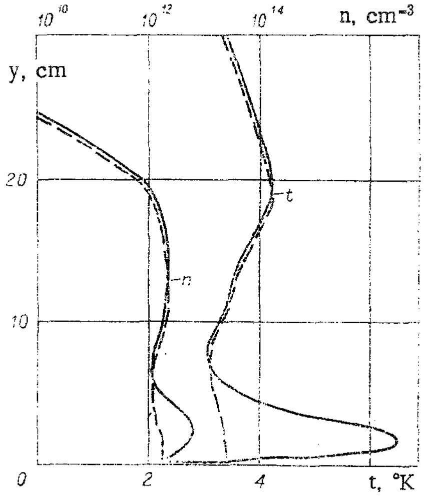

Fig. 2

It is evident that when r_0 = 15 cm the thicknesses of the entropy and boundary layers almost coincide with each other, and when r_0 = 60 cm the thickness of the boundary layer is less than that of the entropy layer. It is evident from a comparison with each other of the distributions illustrated by the dashed and solid curves that in both cases the transport processes exert a significant effect on the formation of the basic characteristics of the plasma along the body. One can say that in the first case (and also in the case in which the thickness of the boundary layer is less than the thickness of the entropy layer [6]) the transport processes determine the order of magnitude of the electron density and exert an appreciable effect on the temperature distribution in the ionized part of the flow field. In the case of a highly blunted body (r_0 = 60 cm) the transport processes make a relatively small contribution to the integrated flux of the electron density but exert a significant effect on the heating of the boundary layer of the gas. Taking this effect into account is especially important in connection with the calculation of the viscous subregion of the near wake formed by the thin boundary layer of the gas.

Data referring to the plasma parameters in wakes behind bodies with r_0 = 60, 15, and 4 cm are presented in Figs. 3-5; curves 1-3 correspond to these versions.

The radial coordinate divided by the diameter of the bottom cutoff D is plotted along the ordinate in Fig. 3, and the calculated distributions of the electron density and the temperature in the cross section of the wake containing the trailing critical point are shown by the solid curves. The temperature distributions are denoted by open circles. The presence of maxima in the immediate vicinity of the wake axis is associated with the effects of gas drag in the boundary zone of the near wake. The second maxima of the electron density distributions lie in the "nonviscous" region of the wake formed by stream lines passing through the outer part of the boundary layer on the body (which lies above the point M; see [1]) and "repeat" the nonmonotonic nature of the electron density distribution in the boundary layer. One should evidently expect that these maxima will be absent in the region

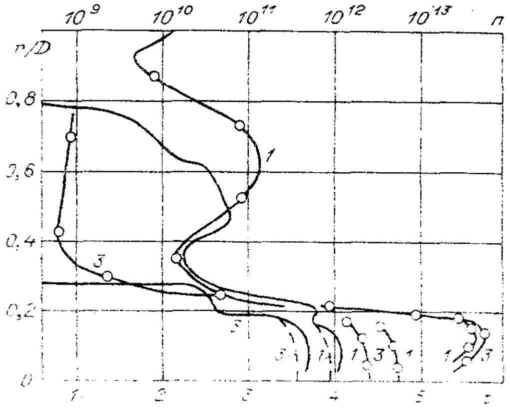

Fig. 3

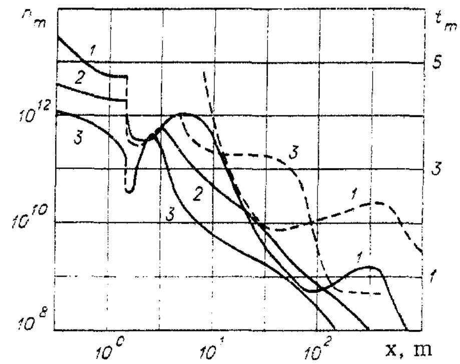

Fig. 4

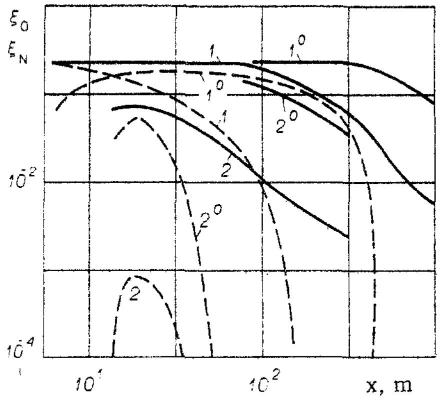

Fig. 5

under discussion when appropriate account is taken of diffusion (which leads to smoothing of the distributions). However, since their magnitude is small in comparison with the first maxima, the diffusion process will not introduce significant corrections to the level of the electron density.

In the case of version 1 the distributions of *n* and *t* have appreciable maxima in the outer region of the wake, which is related completely to the effect of gas drag in the forward shock wave. The temperature increases as one approaches the forward shock wave.

The calculated distributions of the electron density and the temperature near the axis obtained on the assumption of equilibrium of the physicochemical processes with the values of the enthalpy of the viscous subregion of the near wake and the pressure at the trailing critical point found by calculation are shown as dashed curves. If the "equilibrium" and "nonequilibrium" electron density levels are similar to each other, then the corresponding temperature distributions (as well as the concentrations of the neutral components) differ appreciably, which indicates the importance of taking nonequilibrium in the entire region under discussion into account.

The distributions of the maximum values of the electron density n_m along the disturbed region (solid curves) and the maximum values of the temperature t_m along the wake (dashed curves) are shown in Fig. 4. The longitudinal coordinate x figured along the axis of symmetry from the forward critical point is plotted along the abscissa. Their sharp drop in the vicinity of the cutoff of the body and the presence of a maximum near the trailing critical point is characteristic of the electron density distribution. The latter situation is related both to the increase in pressure as one approaches the trailing critical point and to the effect of viscous gas drag in the vicinity of this point.

In accordance with the data of [7], the wake for version 1 was assumed to be turbulent downstream from the trailing critical point, and values of x/D equal to 17 and 100, respectively, were adopted as the transition point for versions 2 and 3.

As follows from the data of Fig. 4, the electron density level at the body and in the initial region of the wake depend significantly on the blunt-end radius of the body. For the cases under discussion the difference in the ionization level amounts to an order of magnitude. Downstream the difference in the ionization level decreases. The drop in the electron density in the region of the distant wake is related to the pressure drop downstream from the trailing critical point (at a distance of the order of ten cone diameters) and to the effects of transport and recombination. In the case of turbulent conditions (version 1) a sharper drop in the electron density occurs, as a result of which the ionization levels for the cases under discussion converge at distances of the order of several tens of cone diameters. Moreover, one should note that the thicknesses of the plasma high-temperature layers along the entire disturbed region depend strongly on the blunt-end radius (increasing as the blunt-end radius increases).

In the case of a highly blunt-end body (version 1) nonmonotonic behavior of both the electron density and the temperature (see Fig. 4) occurs at distances of the order of hundreds of cone diameters, where the ionization level amounts to 10^9 cm^{-3}. These effects are associated with the effect on the boundary viscous (turbulent) region of the flow of a high-entropy nonviscous wake, which is a mixture of the dissociation products of high-temperature air. This fact is illustrated in Fig. 5, where the relative mass concentrations of atomic oxygen ξ_O (solid curves) and atomic nitrogen ξ_N (dashed curves) are given for versions 1 and 2. Curves 1° and 2° refer to the wake axis, and curves 1 and 2 refer to the outer boundary of the turbulent region, which is taken to be the radial coordinate of that point of the wake at which the intermittence coefficient is equal to 0.5.

It is evident that in the case of version 1 (highly blunt-end body) a high level of atomic components is maintained on the outer boundary of the wake right out to a distance of a hundred cone diameters, in contrast to version 2 (and 3 even more). This circumstance leads to a high level of atomic components on the wake axis right out to the distances of several hundred cone diameters. The formation of electrons due to collisions of nitrogen and oxygen atoms in the distant region of the wake starts to exceed their disappearance, which is proportional essentially to the square of the electron density (the sticking process is of little effectiveness here), which leads to nonmonotonicity of the electron density curve in Fig. 4. Along with this the heat liberation per unit volume, which is related to the recombination of atoms, turns out to exceed in this region the decrease of the thermal energy due to thermal conductivity, a result of which is the nonmonotonic behavior of the temperature (dashed curve 1).

It follows from this analysis that in the case of the motion of a body at high altitudes, where laminar flow conditions in the wake occur, the effect of nonmonotonicity of the distribution of the plasma characteristics is expressed more sharply. In the case of a slightly blunt-end body (version 3) the heat liberation on the axis due to recombination of atoms at distances of from ten to hundreds of cone diameters is small (in view of their relatively small concentration). However, since laminar flow conditions in the wake occur in this region, this heat liberation turns out to be similar in amount to the heat loss per unit volume due to molecular thermal conductivity, which results in the appearance in the temperature distribution of a so-called "shelf." Downstream from the transition point the temperature naturally starts to drop.

The effect of a nonmonotonic electron density distribution is absent in wakes behind slightly blunt-end bodies.

It follows from the analysis presented that the blunt-end radius of a body exerts a very significant effect on the plasma characteristics in the disturbed region. This effect is such that an increase in the blunt-end radius leads on the one hand to an obvious increase in the ionization level at the body and in the near region of the wake and can on the other hand lead (as occurs in the cases under discussion) to a sharper drop of the electron density in the distant region of the wake due to a change in the flow conditions. The competing action of transport effects and physicochemical processes in the region of the distant wake can lead both to nonmonotonicity of the distribution of the plasma characteristics along the axis, which is especially characteristic for highly blunt-end bodies, and to convergence of the quantitative plasma characteristics referring to different blunt-end radii of the body.

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