HYPERSONIC FLOW AROUND A BLUNT BODY BY A NONEQUILIBRIUM IONIZED GAS TAKING ACCOUNT OF ADVANCING RADIATION

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The hypersonic flow of a nonequilibrium ionized monatomic radiating gas around a sphere is investigated taking account of the upstream escape radiation from the shock layer (i.e., from the region between the shock and the body surface). A computation of the heating and the preceding ionization of the gas by the radiation in the heated layer affords the possibility of closing the system of equations and determining the value of the degree of gas ionization on the shock front.

The following processes are taken into account in the shock layer:

1) single ionization during an electron–atom collision and its reverse recombination process in a ternary electron–electron–atom collision;

2) single ionization by radiation and photorecombination in the continuous spectrum domain.

The governing process in the warm-up layer, which is characterized by a considerably lower electron temperature and concentration compared to the shock layer, is ionization during absorption of the radiation escaping from the shock layer.

The kinetic gas model from [1] is used. The radiation parameters are computed in the approximation of a locally one-dimensional plane layer [2]. The behavior of the gas-dynamic parameters in the warm-up layer and the influence of the warm-up layer on the field of the shock layer parameters are examined.

The gas-dynamic and radiation fields in the warm-up layer are described by the same system of equations as in the shock layer [2]. However, because of the low temperatures in the warm-up layer, collisional processes as well as radiative recombination can be neglected by considering ionization due to radiative absorption to be the only process occurring. Finally, the ionization originating because of absorption of resonance radiation will also play a known part; however, taking account of this process is a much more complex problem.

In the case under consideration, the relaxation equation and the radiation transfer equation for the warm-up layer take a more simple form in the notation of [2]:

$$\rho \frac{A}{\varepsilon} \frac{\partial \alpha}{\partial \xi} + \rho \frac{v}{r} \frac{\partial \alpha}{\partial \theta} = -\frac{m_a}{\varepsilon} \frac{\partial}{\partial \xi} \int\limits_{\nu_j}^{\infty} (h\nu)^{-1} q_\nu d\nu \tag{1}$$

$$\mu \frac{1}{\varepsilon} \frac{dI_\nu}{d\xi} = -\rho (1-\alpha) \varkappa_\nu I_\nu \tag{2}$$

The boundary conditions for the system of equations in the warm-up layer are the values of the parameters in the undisturbed stream:

$$\alpha = \alpha_\infty, \ W = W_\infty, \ \rho = \rho_\infty, \ T = T_\infty, \ I_{\nu\infty} = 0$$

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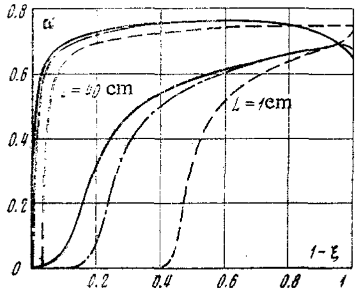

Fig. 1

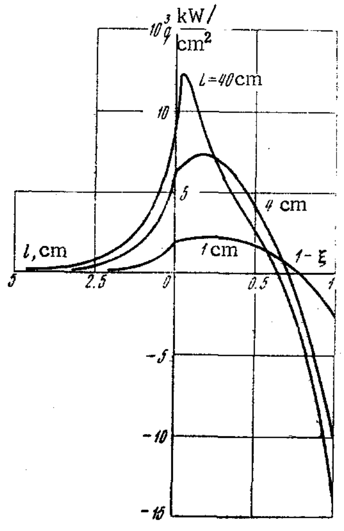

Fig. 2

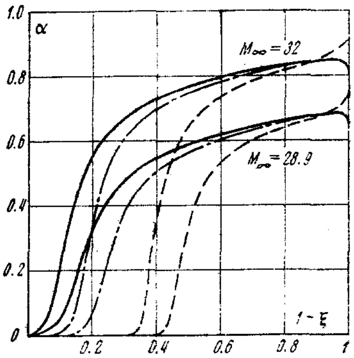

Fig. 3

Equation (2) has the solution

$$I_\nu = C\exp(-\tau_{1\nu}/\mu)\left(\tau_{1\nu} = \varepsilon\int_1^{\xi}\rho(1-\alpha)\varkappa_\nu d\xi\right) \tag{3}$$

where $\tau_{1\nu}$ is the optical coordinate of the warm-up layer measured upstream from the shock surface. The constant of integration C is determined from the condition of continuity of the radiation intensity during passage through the compression shock.

As in [2], the method of solving the problem reduces to a double iteration. The inner iteration cycle consists of finding the shock location and shape for a given radiation field distribution, while the radiation field itself is determined in the outer iteration cycle. A flow without radiation is taken as the initial iteration. There is hence no warm-up layer, and the values of the undisturbed stream parameters are propagated to the shock, where they are the boundary conditions for the system of shock layer equations. After the initial approximation of the flow field in the shock layer has been determined, the radiation field distribution is calculated by means of the gas-dynamic parameters obtained. The value obtained for the radiation intensity (or flux) on the shock affords the possibility of computing the radiation field in the warm-up layer under the assumption that the gas-dynamic field of the warm-up layer remains unchanged. Calculation of the radiation variables upstream is continued until the radiant flux diminishes a given number of time as compared with its value in the shock. The calculated radiation terms are included in the gas-dynamic equations of the warm-up layer in the next iterations, whereupon the flow parameters ahead of the shock, which differ from the undisturbed stream parameters, are found. The outer iteration cycle is continued until both the gas-dynamic and radiation fields agree to a given degree of accuracy in two successive iterations.

The flow around bodies of small radius was examined in order to calibrate the effect of the nonequilibrium and the advancing radiation. The Reynolds criterion is $Re \approx 10^2$ for a minimal value of the radius L = 1 cm, but the shock and boundary-layer thicknesses are, respectively, proportional to Re^{-1} and $Re^{-1/2}$; i.e., the effects of viscosity and heat conductivity should strictly speaking be taken into account in this case. However, taking account of these phenomena jointly with the radiation and nonequilibrium ionization is of great difficulty.

A series of computations of argon flow around a spherical body with radius L (1 cm $\leq$ L $\leq$ 40 cm) and coefficient of surface blackness $\delta = 1$ was carried out in the described formulation on the BÉSM-4M electronic computer. The free-stream pressure, temperature, and degree of ionization were assumed to be, respectively,

$$p_\infty = 0.0002 \text{ atm}, \quad T_\infty = 300° \text{ K}, \quad \alpha_\infty = 10^{-12}$$

Some results of the computations are presented in Figs. 1-5.

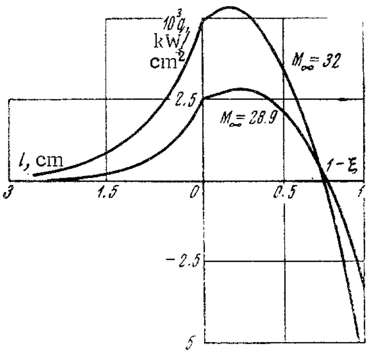

Fig. 4

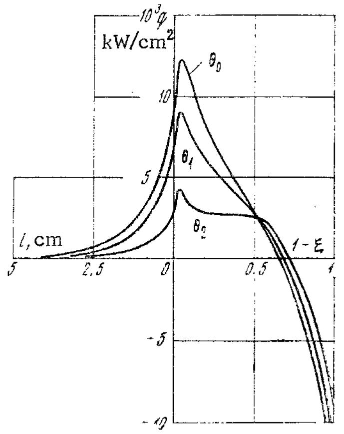

Fig. 5

Solutions obtained taking account of absorption of the advancing radiation by the warm-up layer are shown by the continuous curves. The dashed curves refer to solutions without taking account of radiation, i.e., when only collisional processes are considered. The dash-dot curves are of solutions in the formulation of [2], i.e., taking account of radiation and self-absorption in the shock layer but without taking account of advancing radiation.

Figs. 1 and 2 show the influence of the body size on the nature of the flow at $M_\infty = 28.9$. Profiles of the degree of ionization α on the zero streamline in the shock layer are presented in Fig. 1. It is seen that the flow mode in the shock layer approaches the uniform as the size of the streamlined body increases, as is indicated by contraction in the width of the relaxation zone. The optical thickness of the shock layer τ ($\tau = 0.28$, 0.86, 6.6 for L = 1, 4, 40 cm) hence grows simultaneously, whereupon a significant part of the radiation of the equilibrium domain of the shock layer is absorbed in the relaxation zone without escaping from the shock front. For bodies of small size (or in more rarefied media) the optical thicknesses of the shock layer are considerably less and a part of the shock layer radiation escapes upstream. A comparison between the solutions taking the warm-up layer into account and not taking it into account, for L = 1 and 40 cm, shows that taking account of the warm-up layer is more essential for L = 1 cm.

Profiles of the dimensionless radiant energy flux q along the axis of flow symmetry are shown in Fig. 2. The flux to the right of the vertical axis is constructed as a function of the dimensionless coordinate $\xi = (r - r_0)/(r_* - r_0)$ (r_0 is the radius-vector of the body surface and r_* is the radius-vector of the shock) for which the coordinate line $\xi = 0$ indicates the body surface while $\xi = 1$ is the shock surface. The change in flux to the left of the vertical axis is shown as a function of l, the distance from the shock in centimeters. It is seen in Fig. 2 that the width of the warm-up layer is several centimeters so that for $L \leq 4$ cm it is commensurate with the streamlined body dimensions, but for L = 40 cm the width of the warm-up layer is considerably less than the body radius and is commensurate with the shock layer thickness. It should hence be noted that the absolute shock layer thickness grows as the body radius increases. This results in an increase in the radiant flux q in the shock.

The computations have shown that the profiles of the degree of ionization α follow the change in the flux q qualitatively. Thus, values of α ahead of the shock are, respectively, 0.0019, 0.006, and 0.010 for L = 1, 4, and 40 cm. The gas temperature in the warm-up layer increases 1.5-2-fold in the range of conditions considered. Absorption of radiation by the warm-up layer has practically no effect on the gas flow density and velocity.

Figures 3 and 4 indicate the change in α and q on the zero streamline for L = 1 cm, $M_\infty = 28.9$ and 3 As the free-stream Mach number M_∞ increases, the flow mode approaches the equilibrium, the values of the radiant flux incident on the body surface and escaping into the warm-up layer grow, and the degree of gas ionization in the warm-up layer increases. The values of α ahead of the shock are, respectively, 0.0019 and 0.0033 for the variations considered.

Profiles of the dimensionless radiant flux q are pictured in Fig. 5 for $M_\infty = 28.9$, L = 40 cm for $\theta_0 = 0$, $\theta_1 = 0.25$, and $\theta_2 = 0.5$ radians. It is seen that the radiant flux is a maximum on the zero streamline. As the computational ray θ is moved upward from the axis of symmetry along the enclosure of the body a rapid reduction is observed in the magnitude of the radiant flux while conserving a qualitatively similar dependence $q(\xi)$.

LITERATURE CITED

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