SIMILARITY LAW FOR RADIANT-HEAT-TRANSFER COEFFICIENT FOR A BODY IN A HYPERSONIC FLOW

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The flow of radiating gas around a blunt body with intense vaporization is analyzed. Calculations are made for air and a hydrogen–helium mixture. Universal relations between the radiant-heat-transfer coefficients and the scintillation parameter are derived.

In recent years, there has been considerable interest in the investigation of the radiant heating and mass entrainment of blunt bodies in hypersonic motion in gases. Because this is a complex, multicomponent problem, various approaches have been used for its solution. A long series of works by Karasev and his colleagues [1-3] considered radiant–convective heating and vaporization in the vicinity of the forward critical point, taking into account the diffusion of various components of the dissociated and ionized inflowing gas and the vaporization products of the body. In [4] the flow around the smooth heat region of a body with vaporization in an injected current of equilibrium air was analyzed. It was shown that when viscosity is taken into account the distribution of radiant fluxes over the surface is only slightly changed in comparison with calculations of nonviscous flow. A detailed calculation of viscous flow around a blunt body with a carbon-phenol-plastic surface was made in [5]. Examples of flow with a given rate of gas injection (air or carbon-phenol-plastic vapor) and with the current formed as a result of sublimation are given. Comparison of the data of [5] with the results of the present work for the thickness of the shock layer and the vapor layer, the radiant flux, and the profiles of the parameters in the shock layer and the vapor layer show satisfactory agreement. This again confirms that in the range of flow parameters in which radiant heating leads to considerable vaporization of the material, viscosity does not play a decisive role even in determining the quantitative characteristics.

Systematic calculations of the flow of a hydrogen–helium mixture around bodies of various shapes in a strong current from the surface were made in [6, 7]. The change in shape of a body as it moves through a planetary atmosphere was investigated. The flow problem was solved within the framework of the ideal-gas model.

Thus, the literature reveals considerable experience in the solution of problems of the flow around a body in the presence of radiant heating and intense vaporization. For the further solution of practical problems of radiant heating, it would be useful to have simple correlational dependences, which may be obtained from the available numerical solutions.

Consider hypersonic flow around a blunt body. The radiation of gas behind the leading shock wave is incident on the surface of the body, leading to partial vaporization of the surface. The flow diagram is shown in Fig. 1. The incoming gas, after compression in the shock wave s, moves in the shock layer 1; the vaporization products flow in layer 2 between the contact surface c and the surface of the body w. Motion over the whole of the perturbed region is described by the well-known equations of radiational gasdynamics [8].

The usual Rankine–Hugoniot relations are taken as the boundary conditions at the shock wave. The gas in front of the shock wave does not radiate, so that the boundary condition for the radiation intensity takes the form $I^{+}_{\nu s} = 0$ (the subscript + denotes the direction towards the body in the flow). At the contact surface the conditions of impenetrability and equality of the pressure apply:

$$v_{n1} = v_{n2} = 0,\ p_1 = p_2 \tag{1}$$

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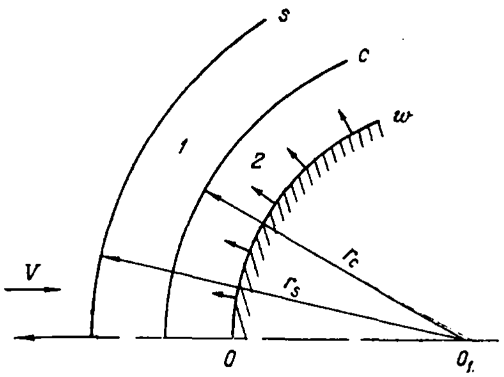

Fig. 1. Flow diagram.

as well as the continuity condition for the radiation. Further, it is assumed that the surface of the body vaporizes in equilibrium conditions. If heat removal inside the body is neglected, the boundary conditions at the body take the following form

$$p_w = f(T_w),\ (\rho v_n)_w H^* = q_w^+(1 - k_w) - \varepsilon_w \sigma T_w^4,$$
$$I_{\nu w}^- = \varepsilon_w B_{\nu w} + I_{\nu w}^+ k_w. \tag{2}$$

Here H* is the latent heat of sublimation of the material; ε_w and k_w are the emissivity and reflection coefficient of the wall.

The complete system of equations is solved by an iterational method. Since the thickness of layers 1 and 2 is small in comparison with the radius of curvature of the body, the approximation of a local plane layer is adopted in taking account of the angular distribution of the radiation. By joint solution of the equations of gas motion and radiation transfer, the effect of radiational cooling may be correctly taken into account, i.e., the change in internal energy (temperature) of the gas as a result of radiant-energy transfer, in particular, the radiation yield from the volume occupied by high-temperature gas.

The values of the concentration of the dissociated-gas components and the thermodynamic functions at each point of the flux are determined by numerical solution of the complete system of equations of thermodynamic equilibrium. The total absorption coefficient of unit volume of gas mixture is calculated from the formula

$$\varkappa_\nu = p \sum_{i=1}^{N} \varkappa_{\nu i} x_i (p,\ T). \tag{3}$$

Here $\varkappa_{\nu i}$ is the absorption coefficient due to all optical transitions for the i-th component; x_i is the molar concentration of the i-th component. The value of $\varkappa_{\nu i}$ depends on the frequency and temperature. In the present work, $\varkappa_{\nu i}$ is calculated using simple analytic approximations of tabular data. Experience with calculations has shown that this approach to the calculation of the total optical characteristics of gas mixtures of complex composition is the most rational for the numerical solution of problems of radiational gas dynamics on a computer. In this way, the absorption coefficient in Eq. (3) may be calculated to satisfactory accuracy without particular difficulty. Examples for equilibrium air at $T = 10^4$°K, p = 1 atm, and equilibrium helium-hydrogen mixture with $x_\infty(H_2) = 0.86$, $x_\infty(He) = 0.14$, at $T = 1.5 \cdot 10^4$°K, p = 6 atm, are shown in Fig. 2. The points in Fig. 2a correspond to the tabular data of [9] and the curve shows the approximation of [10]. The continuous curve in Fig. 2b shows the results of detailed calculations by Plastinin and the dashed curve the results of approximation of these tables.

There have been numerous calculations of the flow of radiating air and H_2 + He mixture around a body whose surface consists of carbon impregnated by phenol resin, with a heat of sublimation $H^* = 3675 + 601 \exp(-0.0983 p_w)$ cal/g [14]. An example of the temperature distribution in the shock layer and the vapor layer is shown in Fig. 3 (the value of T is re-

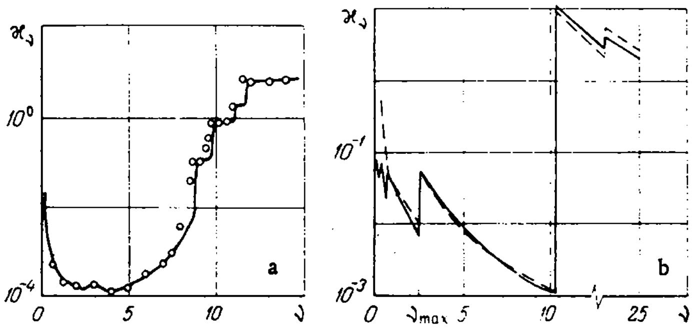

Fig. 2. Tabular and approximation curves of absorption coefficients of air (a) and a helium-hydrogen mixture (b); ν, 10^4 cm^{-1}; $\varkappa_\nu$, cm^{-1}.

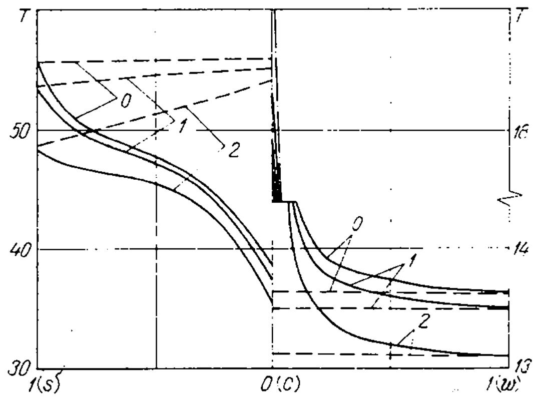

Fig. 3

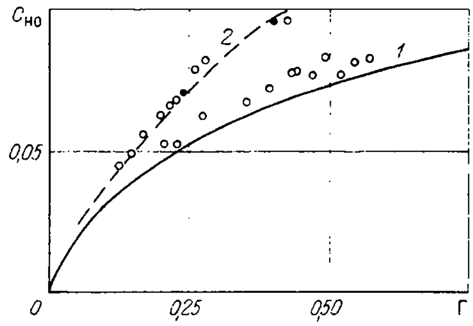

Fig. 4

Fig. 3. Temperature distribution in shock layer and vapor layer.

Fig. 4. Dependence of radiant-heat-transfer coefficient on scintillation parameter.

ferred to T_∞ = 300°K). The values of the argument ξ = 1(s), 0(c), and 1(w) refer to the shock wave, the contact surface, and the wall, respectively. Here $\xi = (r - r_c)/(r_s - r_c)$ in layer 1 and $\xi = (r - r_c)/(r_w - r_c)$ in layer 2. Curves 0, 1, and 2 give temperature profiles along the rays θ = 0, 0.3125, and 0.625. The dashed curves show the same distributions without taking account of radiational cooling. The radiational yield from the shock layer leads to considerable cooling of the gas, while absorption predominates in the vapor layer, so that the temperature increases significantly with approach to the contact surface (for convenience, different scales are used on the ordinate on the left-hand and right-hand sides of Fig. 3).

In some previous works (see [11, 12], for example), it was shown for the example of air that the radiant-heat-transfer coefficient at the critical point $c_{h_0} = q_c^{+}/(1/2)\rho_\infty U_\infty^3$ is a universal function of the scintillation parameter $\Gamma = 2q_{is}/(1/2)\rho_\infty U_\infty^3$, where q_{is} is the radiant flux from the isothermal shock layer. The results of the given calculations provide new initial material for improving the accuracy of this important dependence. Curve 1 in Fig. 4 shows the approximation of [11], obtained on the basis of the solution of the problem taking account of viscosity; the points along curve 1 show the results of the calculations in [12]. Thus, taking account of transfer phenomena leads to very little distortion of the given universal dependence. Curve 2 in Fig. 4 shows the approximation of analogous data for the flow of H_2 + He mixture. The points on curve 2 show the results of the present calculations; the filled points correspond to the flow of pure H_2 [13]. It is clearly seen that the universal dependence is considerably different for gas mixtures with different thermodynamic and optical characteristics. Curves 1 and 2 may be represented, with good accuracy, by the simple analytic dependence

$$c_{h_0} = a\Gamma^b, \tag{4}$$

where a = 0.10, b = 0.47 for air, and a = 0.186, b = 0.69 for H_2 + He mixture. Approximate relations of the type in Eq. (4) may be used to hasten the convergence of the iterational process used to solve the problem in the complete formulation.

NOTATION

v, velocity; p, pressure; x, molar concentration; T, temperature; H*, latent heat of sublimation; I, radiation intensity; k, reflection coefficient of the wall; B_1, Planck function; c_h, radiant-heat-transfer coefficient; U_∞, velocity of incoming flow; a, b, parameters of correlational dependence; ρ, density; q, radiant flux; ε, emissivity; $\varkappa_\nu$, absorption coefficient; ξ, transformed coordinate; Γ, scintillation parameter.

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