SCREENING OF RADIATIVE HEAT FLUX BY THE INJECTION OF PRODUCTS OF THE DESTRUCTION OF ASBESTOS PLASTIC IN HYPERSONIC FLOW OVER A SPHERE

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The variation of the coefficient of screening along the generatrix and the influence of the mode of flow in the boundary layer on its value are analyzed on the example of the flow of a $CO_2 + N_2$ mixture over a sphere of asbestos plastic.

The process of transformation (screening) of the radiation flux emitted by the high-temperature region of flow by the relatively cool layer of ablation products of the material plays an important role in the formation of the thermal regime at the surface of a body over which a high-enthalpy stream of radiating gas flows. Because of the limited possibilities for the experimental study of the problem of radiative-convective heat exchange in a shock layer, research based on numerical modeling acquires special importance. Since the screening of radiant fluxes occurs mainly in flow regions in which a whole series of complicated hydrodynamic and physicochemical processes take place (chemical reactions, photon emission and absorption, and molecular transfer phenomena: viscosity, heat conduction, diffusion, etc.), the initial physical model must make sufficiently full allowance for the most important of these processes. At the same time, the formal demand of completeness of the physical description is naturally associated with complication of the mathematical methods of solving the problem. Therefore, in the choice or development of methods of solution one must consider that their accuracy corresponds to the validity and the limits of applicability of the basic physical premises.

The presently existing methods of numerical investigation of a radiating shock layer near the front surface of a blunt body with allowance for processes of molecular transfer consist, as a rule, of the formal combining of algorithms for solving the gas-dynamic problem and for calculating the selective-emission field and the characteristics of ablation of the heat-shield material (HSM) [1, 2]. This predetermines a certain limitation on the possibilities of using such methods to carry out a calculated-parametric investigation. An approach using a combined formulation [3, 4] has definite advantages from the point of view of increasing the economy of the calculation methods.

Its essence consists in the successive separate solution of the equations of inviscid flow of a radiating gas around in impermeable body of a given shape and the boundary-layer equations with boundary conditions at the surface in the form of equations describing the thermochemical destruction of the HSM. As a result of the solution of the first problem one finds the distributions of the temperature, pressure, tangential velocity, and spectral characteristics of the radiation along the front surface. These are used as the boundary conditions in the integration of the equations for the laminar or turbulent boundary layer. As a result of their solution one determines the values of the radiative and convective heat fluxes to the surface, as well as the rate of HSM ablation. With allowance for the displacement thickness of the boundary layer, one determines the new shape of the impermeable body, and the problem of inviscid flow over it is solved anew. The procedure is repeated until convergence.

Acceleration of the solution of the problem in such an approach, also used in the present work, is achieved mainly through the solution of Euler's equations in the boundary layer instead of the more complicated equations of a viscous, heat-conducting, radiating shock layer. Moreover, because of the relative thinness of the boundary layer one can resort to the procedure of calculating the inviscid part a small number of times.

Moscow Physics and Technology Institute. Translated from Inzhenero-Fizicheskii Zhurnal, Vol. 46, No. 2, pp. 303-308, February, 1984. Original article submitted September 15, 1982.

 0022-0841/84/4602-0228$08.50

TABLE 1. Parameters of the Analyzed Variants of Flow Over a Body

No.	ρ_∞, kg/m^3	V_∞, km/sec	p_s, 10^5 N/m^2	T_s, 10^3°K
1	$9{,}516\cdot10^{-4}$	11,04	1,08	10,84
2	$4{,}145\cdot10^{-3}$	10,58	4,34	10,58
3	$2{,}086\cdot10^{-2}$	8,32	13,49	8,39

A considerable increase in the efficiency of the numerical algorithm within the framework of the combined formulation of the problem is possible in the case when the method of radiation disturbance proposed in [5] is used to calculate the inviscid radiating shock layer.

For the range of flow conditions under consideration, in which radiation is the dominant mechanism of heat exchange in the shock layer, the mode of developed turbulent flow occurs over the greater part of the front surface of a sphere. The existing uncertainty in the models describing turbulent heat and mass transfer in a high-temperature boundary layer in the presence of injection and radiative transfer elicits interest in the question of the influence of the calculation model on the characteristics of heat and mass exchange. The degree of this influence can be judged on the basis of a comparison of the results of calculations made for developed turbulent (in accordance with one of the models) and laminar flows.

The main purpose of the present work consisted in the calculated-parametric investigation and physical analysis of the laws of screening of the radiative flux by the laminar and turbulent boundary layer at the front surface of a sphere.

We present the results of systematic calculations of the radiative—convective heat exchange over a considerable part of the front surface of a sphere ($0° \le \theta \le 60°$) over which a hypersonic stream of a mixture of 98% CO_2 + 2% N_2 (by volume) flows. We considered the following range of the determining parameters: $10^{-4} < \rho_\infty \le 10^{-2}$ kg/m^3, $7 \le V_\infty \le 12$ km/sec, $0.5 \le R \le 2$ m. As the boundary conditions at the surface of the sphere we considered the quasistationary thermochemical destruction of asbestos plastic [6]. We used a model of the properties of turbulent heat and mass transfer allowing for the influence of the injection factor [2]. The transfer properties of the chemically equilibrium mixture formed by products of reactions between components of the atmospheric and injected gases were calculated by the method presented in [7] using the thermodynamic calculation program of [8]. The optical properties of the heated atmospheric gas and of the products of destruction of asbestos plastic were calculated using the absorption cross sections of the individual components from [9, 10].

On the example of three typical cases of flow over a sphere with a radius R = 1 m by a hypersonic stream of CO_2 + N_2 mixture (see Table 1) let us examine the variation of the coefficient of screening $E(\theta)$ of the radiant flux along the generatrix of the sphere (Fig. 1). This coefficient consists of the ratio of the radiant fluxes reaching the surface of the body and the external limit of the boundary layer:

$$E(\theta) = q_w(\theta)/q_e(\theta), \quad q(\theta) = \int\limits_{0,05\,\mu m}^{1\,\mu m} q_\lambda(\theta)\, d\lambda. \tag{1}$$

The solid curves in the figures pertain to the turbulent mode of flow in the boundary layer and the dashed lines to the laminar mode.

In analyzing the data presented, as well as analogous data obtained for other conditions of flow over a body from the above-indicated ranges of values of ρ_∞, V_∞, and R, one can note the following. It is known that in an inviscid shock layer around a sphere there is great variation of the pressure, temperature, and tangential velocity component in the shock layer as θ increases, which results, in particular, in a considerable decrease in the radiant flux reaching the boundary layer and in the rate of ablation of the asbestos plastic occurring through thermochemical destruction. Despite the clearly expressed nonuniformity of the flow and heat-exchange parameters along the generatrix of the sphere, however, in certain cases of practical interest the screening coefficient $E(\theta)$ varies little in the interval of $0° \le \theta \le 60°$ (curves 3 in Fig. 1). The relatively weak influence of the mode of flow in the boundary layer on $E(\theta)$ also attracts attention.

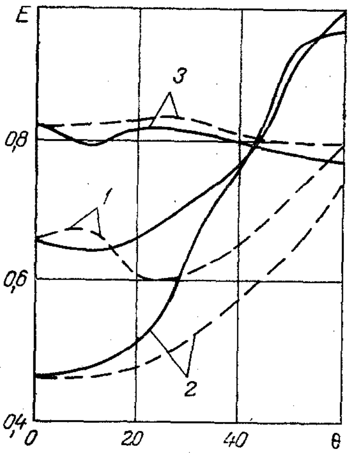

Fig. 1

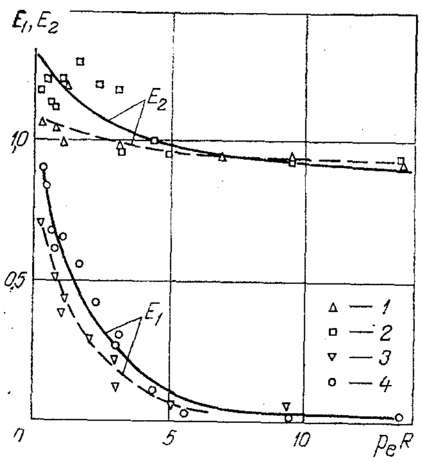

Fig. 2.

Fig. 1. Distribution of the coefficient of screening of radiant flux over the generatrix of a sphere of radius R = 1 m for the flow conditions presented in Table 1. θ, deg.

Fig. 2. Screening coefficients E_1 and E_2 as functions of the parameter p_eR, 10^5 N/m; calculated points from the range of angles $0 \leq \theta \leq 60°$; 1, 3) laminar mode; 2, 4) turbulent mode of flow in the boundary layer; 1, 2) E_2; 3, 4) E_1.

To clarify the results obtained, let us consider the spectral characteristics of the process of transformation of radiant flux in the boundary layer. For this purpose it is convenient to divide the entire spectrum into two regions — short-wavelength ($\lambda \leqslant 0.2$ μm) and long-wavelength ($\lambda \geqslant 0.2$ μm) — in which the coefficients of absorption of the high-temperature gas differ considerably.* In the wavelength interval of $\lambda \leqslant 0.2$ μm practically all the gas components in the shock layer have large cross sections of photoionization from the ground and low excited states; the optically active fourth positive (4+) electronic band of the CO molecule is also located here. As a result, the radiant flux arriving from the inviscid part of the shock layer at these wavelengths is efficiently absorbed. The transformation of radiant flux in the spectral region of $\lambda \geqslant 0.2$ μm is due mainly to transitions in the vicinity of the centers of the bands of molecules included in the composition of the destruction products of asbestos plastic. For the range of conditions under consideration the maximum optical depth of the boundary layer due to these transitions does not exceed 0.3.

By analogy with the coefficient of screening of radiant flux in the entire spectral section under consideration, we introduce the screening coefficients E_1 and E_2 in selected intervals,

$$E_1(\theta) = q_{1w}(\theta)/q_{1e}(\theta), \quad E_2(\theta) = q_{2w}(\theta)/q_{2e}(\theta),$$
$$q_1(\theta) = \int\limits_{0,05\,\mu\text{m}}^{0,2\,\mu\text{m}} q_\lambda(\theta)\,d\lambda, \quad q_2(\theta) = \int\limits_{0,2\,\mu\text{m}}^{1\,\mu\text{m}} q_\lambda(\theta)\,d\lambda. \tag{2}$$

The quantity E can be expressed through E_1 and E_2,

$$E = E_2 + A(\theta)(E_1 - E_2), \tag{3}$$

where $A(\theta) = \int\limits_{0,05\,\mu\text{m}}^{0,2\,\mu\text{m}} q_{\lambda e}(\theta)\,d\lambda / \int\limits_{0,05\,\mu\text{m}}^{1\,\mu\text{m}} q_{\lambda e}(\theta)\,d\lambda$ characterizes the spectral composition of the radiation arriving at the boundary layer.

In [5] it was shown that approximate self-similarity of the function A(θ) with respect to θ, i.e., $A(\theta) \simeq A(0)$, occurs in a wide range of variation of the parameters of flow of air and of a $CO_2 + N_2$ mixture over a sphere. Consequently, it follows from (3) that the

*The neighborhoods of the centers of strong lines are an exception; they do not make an appreciable contribution to the process of radiation screening in the boundary layer, however [11].

character of the function $E(\theta)$ is determined mainly by the variation of the coefficients E_1 and E_2 along the generatrix of the sphere.

An analysis of the calculated results showed that for the entire range of conditions under consideration these coefficients can be taken as functions of a single argument: the product of the pressure p_e in the given section of the boundary layer times the radius R of the sphere (Fig. 2). Here it is important that for both the laminar and the turbulent modes of flow in the boundary layer the coefficient E_2 of screening of "long-wavelength" radiation varies by no more than 30% in the range of $10^4 \leqslant p_eR \leqslant 20 \cdot 10^5$ N/m (Fig. 2). For example, this results in the fact that the maximum difference between $E_2(\theta)$ and $E_2(0)$ does not exceed 10-15% in the range of angles $0 \leqslant \theta \leq 60°$.

At the same time, it is seen from Fig. 2 that the coefficient E_1 varies greatly as the parameter p_eR increases: $E_1 \lesssim 1$ for small values of p_eR, whereas for $p_eR \gtrsim 5 \cdot 10^5$ N/m the radiation arriving at the boundary layer is almost entirely absorbed.

For a sphere with a given radius R, greater distance from the critical point along the generatrix corresponds to a decrease in the product p_eR. Therefore, on the basis of the foregoing, we can conclude that a pronounced dependence of E on θ should be expected under the conditions when there is sufficiently strong variation of the coefficient $E_1(\theta)$, i.e., for $p_eR \lesssim 5 \cdot 10^5$ N/m. Of the variants given as examples, this range corresponds to modes 1 and 2. Under flow conditions characterized by a sufficiently high value of $p_eR \gtrsim 5 \cdot 10^5$ N/m not only at the critical point but also in flow regions remote from it (mode 3, for example), the coefficient E varies along the generatrix of the sphere. In this case, as follows from (3), its numerical value proves to be close to $[1 - A(\theta)]$.

Now let us examine the influence of the mode of flow on the screening properties of the boundary layer. In each cross section of the boundary layer the average transverse distributions of velocity, temperature, and the concentration of the chemical elements prove to be qualitatively different in the cases of the turbulent and laminar modes of flow. The geometrical thicknesses of the boundary layers also differ considerably. For mode 2 at $\theta = 60°$, for example, the thickness of the turbulent boundary layer exceeds the thickness of the laminar one by more than an order of magnitude.

As seen from Fig. 2, however, the difference in the values of the coefficients E_1 and E_2 in the flows being compared proves to be slight, with $E_1^t \gtrsim E_1^l$ and $E_2^t \gtrsim E_2^l$. The reason for such a dependence of E_1 and E_2 on the mode of flow consists in the following. In both cases near the surface there is an absence of components capable of appreciably transforming radiation arriving from the inviscid part of the shock layer in the interval of $\lambda \gtrsim 0.2$ μm. Under the conditions being considered, in particular, this results in the fact that $|E_2 - 1| \lesssim 0.2$ and $|E_2^t - E_2^l| \lesssim 0.1$ (Fig. 2). A certain clearing of the turbulent boundary layer in comparison with the laminar one in both spectral intervals is due to the more intense emission of molecular components in the high-temperature part of the turbulent boundary layer. We emphasize that the small difference between E_1^t and E_1^l is specific for the conditions when the concentrations of optically active components are significant both in the injected gas and in the inviscid section. In the problem under consideration the CO molecule is such a component.

Since the functions $A(\theta)$ practically coincide in the cases of laminar and turbulent boundary layers, the indicated ratios of the components E_1^t and E_1^l and of E_2^t and E_2^l result also in a relatively weak dependence of the total screening coefficient E on the mode of flow over considerable sections of the front surface of a sphere (see Fig. 1).

It must be emphasized that the main physical factor resulting in the practical coincidence of the screening properties of the boundary layer in the modes of flow being compared is the high optical transparency of the gaseous products of destruction of asbestos plastic in the spectral region in which most of the radiant energy arrives at the boundary layer from the inviscid section ($\lambda \gtrsim 0.2$ μm), which occurs for $p_sR \gtrsim 5 \cdot 10^5$ N/m in the range of conditions under consideration. When a material whose composition includes substances capable of efficiently absorbing radiation of these wavelengths in the gaseous phase is used as the heat-shield coating, the difference in the flow structure in the turbulent and laminar modes can result in a more pronounced difference in the screening properties of the boundary layers.

NOTATION

λ, wavelength; θ, angular coordinate along the generatrix of the sphere; ρ, density; V, velocity; p, pressure; T, temperature; R, radius of the sphere; q, radiant flux; q_λ, spectral density of radiant flux; E, coefficient of screening of the radiant flux by the boundary layer; A, fraction of radiation arriving at the boundary layer from the inviscid section in the spectral interval of $\lambda < 0.2$ µm. Subscripts: w, surface of body; e, external part of boundary layer; s, behind the direct shock wave; ∞, oncoming stream; t, turbulent; l, laminar.

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