ENGINEERING METHOD OF COMPUTING THE RADIATION FLUX TO A PERMEABLE SURFACE UNDER AERODYNAMIC HEATING CONDITIONS

M. N. Rolin and N. L. Yadrevskaya

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Formulas are proposed for the computation of the radiation heat transfer at the frontal point of an axisymmetric blunt body with a carbon-based destructible coating around which a hypersonic air stream flows.

At the present time the main source of data on radiation—convective heat transfer in a hypersonic flow are the results of numerical modeling based on the joint solution of the gas-dynamics and radiation transport equations [1, 2]. It should be noted that the use of such an approach is associated with the creation of complicated program complexes and the execution of costly computations on powerful electronic computers. The necessity for a simplified methodology to compute the radiation—convective heat transfer on blunt body surfaces during the destruction of heat shield coatings based on carbon [3] often occurs in engineering practice. A number of papers [4-7] are known in which attempts were made to obtain generalized dependences for the radiation flux to a permeable surface. However, the possibilities for using their results are limited. In some cases this is related to the narrowness of the range of conditions investigated, and in others to the utilization of simplified physical models in the computations from whose results generalization were constructed. Only the integral values of the fluxes were determined in all the papers known, and from the practical point of view their spectral distribution is also of interest. Also essential is the circumstance that in the time since the publication of these papers refined data on the optical properties of the products of coating destruction have been obtained [2].

Numerical modeling of the radiation—convective heat transfer at the stagnation point of an axisymmetric blunt body with a destructible carbon coating around which a hypersonic air stream flows is performed in this paper for the following range of parameters: $V_\infty = 11\text{-}18$ km/sec; $P_s = (0.3\text{-}10)\cdot 10^5$ Pa, $R = 0.2\text{-}1$ m. The injection parameter $f = G_w/(\rho_\infty V_\infty)$ was found from the energy flux balance conditions on the body surface. Therefore, the mode of steady thermal destruction of the coating as a result of sublimation and surface combustion was modeled. Forty-five modifications of the computation were performed for values of the flow parameters distributed uniformly in the above-mentioned range.

The general physical model of the processes took account of radiation transport in a continuous spectrum and in spectrum lines, the influence of viscosity, heat conduction, multicomponent diffusion, and equilibrium chemical reaction effects [8, 9]. Energy transport by radiation was computed by the method of numerical integration in the spectrum. Modern data on the optical absorption sections for the carbon destruction products were used in the computations [2].

Partition of the compressed layer into two domains, an external one including the zone of the high-temperature air flow detected in the compression shock, and an internal one to which the flux of coating destruction products and the mixing zone belong, was introduced to construct the engineering method generalizing these results. For definiteness the point e for which $\alpha_{ce} = 0.05\alpha_{cw}$ was considered the domain boundary.

Separate large-scale spectrum bands were extracted, in each of which the optical properties of the destruction products and the high-temperature air possess characteristic features: 1) $\lambda = 0.05\text{-}0.11$ μm; 2) $\lambda = 0.11\text{-}0.144$ μm; 3) $\lambda = 0.144\text{-}0.19$ μm; 4) $\lambda = 0.19\text{-}0.33$ μm; 5) $\lambda = 0.33\text{-}0.63$ μm; 6) $\lambda = 0.63\text{-}10$ μm. Upon introduction of this partition, the location of the nitrogen, oxygen, and carbon photoionization thresholds with the energetic states of the main electron configuration, the location of the band systems of the molecules C_2 and

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A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 55, No. 5, pp. 763-767, November, 1988. Original article submitted May 4, 1987.

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TABLE 1. Approximation Coefficients for q_{ei}^{p}

i	a_i	b_i	c_i	d_i	e_i	f_i
1	$-2,707\cdot 10^{-2}$	$-0,2413$	$-1,719$	$0,9023$	$-0,6056$	$0,7031$
2	$-2,709\cdot 10^{-3}$	$-0,06785$	$-0,9203$	$0,9838$	$-0,5401$	$0,3427$
3	$-5,643\cdot 10^{-2}$	$0,06763$	$-0,9163$	$0,3247$	$0,4924$	$0,5054$
4	$-7,541\cdot 10^{-4}$	$0,00041$	$-0,4950$	$0,8355$	$1,0941$	$0,1684$
5	$3,347\cdot 10^{-2}$	$-0,2611$	$-0,3126$	$0,9072$	$-1,8431$	$-0,0931$
6	$4,062\cdot 10^{-2}$	$-0,3162$	$-0,2454$	$0,3730$	$-0,6283$	$-0,1133$

C_3 that predominate in the destruction products, and the locations of the most intensive nitrogen and oxygen lines were taken into account.

The radiation flux to the surface in the i-th spectrum band is considered as the flux from the high-temperature domain partially shielded by the destruction products. This permits its representation in the form

$$q_{wi}^{p} = q_{ei}^{p} K_i. \tag{1}$$

The quantity K_i has the meaning of a radiation shielding factor.

It is established [10] that the integral radiation flux to an impermeable surface can be approximated by expressions of the form

$$q_w^p = q_a^p F(\Gamma),$$

where q_a^p is the radiation flux from adiabatic compressed layer. The thickness of the adiabatic compressed layer, its temperature and pressure are computed by means of known hypersonic aerodynamics formulas [11]. The dimensionless quantity Γ, called the radiation–convection interaction parameter, is defined as $\Gamma = 4q_a^p/(\rho_\infty V_\infty^3)$. The form of the function $F(\Gamma)$ is selected by using the values of q_w^p obtained in the numerical modeling.

The quantity q_{ai}^p, the radiation flux from the adiabatic compressed layer in the i-th spectrum band, is introduced into the consideration in this paper and the flux from the external domain of the compressed layer is represented in the form

$$q_{ei}^{p} \approx q_{ai}^{p} F_i(\Gamma, \Pi). \tag{2}$$

The quantities q_{ai}^p are computed from data for the optical properties of air at high temperatures [12, 13]. The authors of the paper could obtain detailed tables of q_{ai}^p to assure the possibility of interpolation.

In this case the ratio q_{ei}^p/q_{ai}^p is not a function of just the parameter Γ, and a quantity $\Pi = P_s R/V_\infty$, characterizing the optical thickness of the compressed layer, is also introduced. The expression

$$F_i(\Gamma, \Pi) = \exp\left[(a_i + b_i\Gamma)\Pi^{c_i + d_i\Gamma} + e_i\Gamma^{f_i}\right] \tag{3}$$

is selected for the function $F_i(\Gamma, \Pi)$ by empirical means. The approximating coefficients a_i, b_i, c_i, d_i, e_i, f_i (Table 1) are determined by using minimization of the rms value of q_{ei}^p relative to the deviation, as calculated by means of (2) and (3) from values obtained in the numerical modeling. The method of random search [14] was used here.

The formula selected empirically for the function approximating the shielding coefficient K_i as a function of the parameter Π and the dimensionless quantity f has the form

$$K_i(f, \Pi) = \exp\left(\frac{\alpha_i f\Pi}{\beta_i f\Pi + 1} + \gamma_i \Pi^{\delta_i}\right). \tag{4}$$

The rms deviation for q_{wi}^p/q_w^p was minimized to determine the approximating coefficients in this formula. This is associated with the circumstance that values of K_i tend to zero for large f in the shortwave spectrum domain and it turns out to be impossible to obtain a small relative error for q_{wi}^p. Values of the approximating coefficients of (4) are represented in Table 2. The accuracy of computations by means of the formulas proposed was estimated by using the magnitudes of the radiation flux to a surface as obtained in a series of computations for values of V_∞, P_s, R selected from the above-mentioned range but not agreeing as a set with those used in constructing the approximation. The values of f here dif-

TABLE 2. Approximation Coefficients for K_i

i	α_i	β_i	γ_i	δ_i
1	−11,429	0,1761	−0,4425	0,2335
2	− 1,388	0,1266	−0,2416	−0,5053
3	− 2,259	1,7100	−0,1124	−0,3657
4	− 0,545	0,5468	0,2012	−0,1571
5	− 1,547	0,5778	0,5164	−0,2084
6	−0,0424	0,3075	0,0881	−0,2442

TABLE 3. Relative Errors ε in Computing the Radiation Flux to a Surface in the Absence of Injection

V_∞, km/sec	P_s, 10^5 Pa	R, m	ε, %	V_∞, km/sec	P_s, 10^5 Pa	R, m	ε, %
18	0,3	1	4,1	15	3	1	17,7
18	1	0,3	0,2	15	10	1	22,1
18	1	1	6,0	12	0,3	1	3,3
18	3	1	29,2	12	1	0,3	12,9
15	0,3	1	1,8	12	1	1	8,1
15	1	0,3	0,9	12	3	1	13,7
15	1	1	7,4	12	10	1	28,3

fered by ±(20-25)% from f*. It is established that the mean error in determining q_w^P by the engineering method is approximately 10%.

Estimation of the possibility of using this method for $f \ll f^*$ is of interest. Such conditions can occur because of nonstationary flow conditions, the presence of internal cooling in the coating or of giving the coating improved reflecting properties. Let us note that for the case of no destruction the shielding coefficient does not equal one. This is due to the presence of absorption in the boundary layer on an impermeable surface for the shortwave bands 1-3 [10]. In this case the coefficient K_i for bands 4 and 5 is greater than one since an increase in the flux in the relatively cold near-wall domain is possible for the long-wave part of the spectrum [7]. An accurate estimate of this effect cannot be obtained within the framework of the approach being developed here and a direct determination of the errors occurring when using the proposed formulas for ultimately small f is required. Errors in computations using (1)-(4) for f = 0 are represented in Table 3. It is seen that these errors are substantial only for large values of the stagnation pressure and the bluntness radius. In this case the engineering method yields exaggerated values of q_w^P.

Extension of the approach described above to a broader range of flow conditions and atmospheric media different from air is of interest.

NOTATION

V_∞, incoming flow velocity; P_s, stagnation pressure; R, bluntness radius; ρ_∞, incoming flow density; G_w, mass flow density through the body surface; f, injection parameter; f*, injection parameter under steady carbon destruction conditions; α_c, mass carbon concentration in the gas; λ, radiation wavelength; q^P, radiation flux density toward the surface; ε, computed error. Subscripts: w, conditions on the body surface; e, conditions at the point separating the compressed layer domains; a, conditions in the adiabatic compressed layer; i, number of the spectrum band.

LITERATURE CITED

1. A. B. Karasev and T. V. Kondranin, Inzh.-Fiz. Zh., 46, No. 1, 77-85 (1984).
2. M. N. Rolin and F. B. Yurevich, Teplofiz. Vys. Temp., 23, No. 2, 340-345 (1985).
3. Yu. V. Polezhaev and F. B. Yurevich, Heat Shield [in Russian], Moscow (1976).
4. A. N. Rumynskii and V. P. Churkin, Zh. Vychisl. Mat. Mat. Fiz., 14, No. 6, 1553-1570 (1974).
5. J. N. Moss, E. C. Anderson, and C. W. Bolz, AIAA Paper No. 671 (1975).

6. L. M. Biberman, S. Ya. Bronin, M. V. Brykin, and A. Kh. Mnatsakanyan, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 3, 129-135 (1978).
7. T. V. Kondranin and I. N. Kuz'minskii, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 5, 71-77 (1978).
8. M. N. Rolin and F. B. Yurevich, Heat and Mass Transfer – VI, Vol. 2 [in Russian], Minsk (1980), pp. 12-23.
9. M. N. Rolin, R. I. Soloukhin, and F. B. Yurevich, Int. J. Heat Mass Transfer, 24, No. 11, 1771-1782 (1981).
10. L. M. Biberman, S. Ya. Bronin, and A. N. Lagar'kov, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 5, 112-123 (1972).
11. V. V. Lunev, Hypersonic Aerodynamics [in Russian], Moscow (1975).
12. L. M. Biberman (ed.), Optical Properties of Hot Air [in Russian], Moscow (1970).
13. V. A. Kamenshchikov, Yu. A. Plastinin, V. M. Nikolaev, and L. A. Novitskii, Radiation Properties of Gases at High Temperatures [in Russian], Moscow (1971).
14. V. G. Karmanov, Mathematical Programming [in Russian], Moscow (1986).

INSTABILITY OF A STEADY-STATE REGIME FOR THE COMBUSTION OF PETROLEUM IN A POROUS MEDIUM

S. P. Fedotov and N. A. Mikhailova

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A system of equations for multiphase nonisothermal filtration is used to examine the problem of dynamic instability, as well as the self-excited oscillations of a plane fuel-combustion front in a porous medium.

In a number of experiments designed to model the process of combustion within a combustion front, we observe variations in the velocity at which the petroleum-combustion front moves [1-3]. The existence of oscillatory instability exhibited by the plane front of steady combustion and the self-excited regular oscillations generated in this way are long since familiar from examples of the combustion of powders and nongaseous systems [4, 5], and from filtration combustion of metals [6]; however, unlike these last examples, no theory has yet been constructed for the instability and self-induced oscillations of a fuel-combustion front in a porous medium. Analytical results in this area have been obtained within the framework of a steady-state postulation of the problem [7, 8]; the nonsteady effects have been investigated primarily with numerical methods [9, 10].

In the general case, the theoretical investigation of the process of combustion within a combustion front must be based on a system of differential equations for multiphase nonisothermal filtration, which includes the continuity equations for petroleum as well as for a multicomponent fuel that undergoes changes as a consequence of oxidation, distillation, cracking, etc., both for water and steam, for an inert gas and an oxidizer pumped into the fuel, for gaseous reaction products, as well as an equation for the temperature and laws of filtration. The complexity of the mathematical analysis of such a system of nonlinear equations is obvious and, therefore, use is normally made of a series of simplifying assumptions (see, for example, the review in [1]).

Statement of the Problem. It is assumed in this paper that the petroleum is an incompressible liquid made up of only a single component and that it enters into the oxidation process in accordance with the reaction $H + \nu_1 O_2 \to \nu_3 \Pi$, where Π denotes the gaseous reaction products. It is assumed that these last exhibit the same thermophysical properties as an oxidizer and an inert gas. We examine the "dry" combustion of the petroleum, achieved solely by forcing air into the interstitial space.

A. M. Gor'kii Ural State University, Sverdlovsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 55, No. 5, pp. 767-775, November, 1988. Original article submitted May 12, 1987.

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