EFFECT OF NONEQUILIBRIUM CHEMICAL REACTIONS ON CONJUGATE HEAT AND MASS EXCHANGE BETWEEN A SOLID BODY AND A MULTICOMPONENT GAS STREAM

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The characteristics of the conjugate heat and mass exchange for a gas stream and a reactive solid body are found and the advisability of using the heat-exchange coefficient is discussed.

The flow over the frontal stagnation point of a model which is free of pores and composed of graphite or electrode carbon is analyzed. A mixture of oxygen, nitrogen, and carbon monoxide flows over the body. The primary and secondary irreversible chemical reactions $C + O_2 = CO_2$ and $C + CO_2 = 2CO$, due to the interaction of the solid body and the oncoming stream, occur at the surface of the material. The product of the secondary heterogeneous reaction, entering the oncoming stream, interacts with the oxygen and the irreversible chemical reaction $O_2 + 2CO = 2CO_2$ develops in the boundary layer. It is assumed that the processes of heat and mass exchange in the gas are quasisteady and that the temperature in the boundary layer does not exceed the temperature of oxygen dissociation. Since the molecular weights of CO, O_2, and N_2 are close, the four-component mixture of CO (1), O_2 (2), CO_2 (3), and N_2(4) is assumed to be an effective binary mixture with the coefficient of binary diffusion of O_2 in CO_2. We will also assume that the heat capacities of the components are constant and identical, and then the mathematically formulated problem comes down to the solution of the following system of equations:

$$(lf''_{\eta\eta})'_{\eta} + ff''_{\eta\eta} = \frac{1}{2}\left(f'^{2}_{\eta} - \frac{\rho_e}{\rho}\right),$$

$$\frac{\rho}{\rho_e} = \frac{(1+\beta\theta_e)\sum\limits_{\alpha=1}^{4}\frac{c_{\alpha e}}{M_\alpha}}{(1+\beta\theta)\sum\limits_{\alpha=1}^{4}\frac{c_\alpha}{M_\alpha}}, \tag{1}$$

$$\left(\frac{l}{\Pr}\,\theta'_{\eta}\right)' + f\theta'_{\eta} = -\mathrm{Dam}\,\frac{M_3}{M_1}\,W(c_1,\,c_3,\,\theta), \tag{2}$$

$$\left(\frac{l}{\mathrm{Sc}}\,c'_{1\eta}\right)'_{\eta} + fc'_{1\eta} = \gamma\,\mathrm{Dam}\,\frac{q_1}{q}\,W(c_1,\,c_3,\,\theta), \tag{3}$$

$$\left(\frac{l}{\mathrm{Sc}}\,c'_{3\eta}\right)'_{\eta} + fc'_{3\eta} = -\gamma\,\mathrm{Dam}\,\frac{q_1}{q}\,\frac{M_3}{M_1}\,W(c_1,\,c_3,\,\theta), \tag{4}$$

$$\left(\frac{l}{\mathrm{Sc}}\,c'_{4\eta}\right)'_{\eta} + fc'_{4\eta} = 0, \tag{5}$$

$$\frac{\partial\theta_s}{\partial\tau} - \gamma\,\frac{\rho_w}{\rho_s}\,(\overline{\rho v})_w\sqrt{\pi_\varkappa}\,\frac{\partial\theta_s}{\partial Y_s} = \frac{\partial^2\theta_s}{\partial Y_s^2} \tag{6}$$

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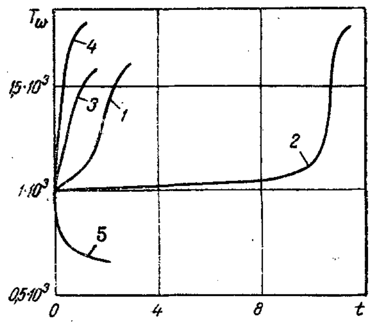

Fig. 1

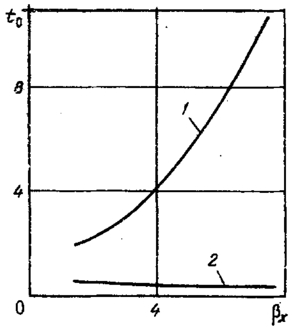

Fig. 2

Fig. 1. Dependence of surface temperature T_w, °K, on the time t, sec, with the initial temperature of the body $T_* = 1000$°K and mass concentrations $c_{2e} = 0.3$ and $c_{3e} = 0.7$ at the outer limit of the boundary layer for different values of the outer parameters: 1) $T_e = 900$°K, $\beta_x = 1406.25$ sec^{-1}; 2) $T_e = 900$, $\beta_x = 7500$; 3) $T_e = 1500$, $\beta_x = 1406.25$; 4) $T_e = 1500$, $\beta_x = 7500$; 5) $T_e = 500$°K, $\beta_x = 1.5\cdot10^4$ sec^{-1}.

Fig. 2. Dependence of heterogeneous ignition time t_0, sec, on β_x, sec^{-1}, with mass concentrations $c_{2e} = 0.3$ and $c_{3e} = 0.7$ at the outer limit of the boundary layer for different values of T_e: 1) $T_e = 900$°K; 2) 1500.

with the boundary and initial conditions

$$f'_\eta(\infty) = 1, \quad \theta(\infty) = \theta_e, \quad c_\alpha(\infty) = c_{\alpha e}, \tag{7}$$

$$\frac{\lambda_w}{\lambda_e}\cdot\frac{\rho_w}{\rho_e}\sqrt{\frac{2\Delta}{\mathrm{Pr}_e}}\,(\theta'_\eta)_w + \frac{\rho_w}{\rho_e}\left[c_{2w}\exp\frac{\theta_w}{1+\beta\theta_w} - a\frac{M_1}{M_3}\,\frac{q_2}{q_1}\,c_{3w}\exp\frac{b_1\theta_w}{1+\beta\theta_w}\right]$$
$$-\pi_\sigma[(1+\beta\theta_w)^4-(1+\beta\theta_e)^4] = -K_\varepsilon\left(\frac{\partial\theta_s}{\partial Y_s}\right)_w, \tag{8}$$

$$-\frac{\lambda_w}{\lambda_e}\,\mathrm{Le}_w\sqrt{\frac{2\Delta}{\mathrm{Pr}_e}}\,(c'_{1\eta})_w + \gamma c_{1w}(\overline{\rho v})_w = 2\gamma a\frac{M_1}{M_3}\,c_{3w}\exp\frac{b_1\theta_w}{1+\beta\theta_w}, \tag{9}$$

$$-\frac{\lambda_w}{\lambda_e}\,\mathrm{Le}_w\sqrt{\frac{2\Delta}{\mathrm{Pr}_e}}\,(c'_{3\eta})_w + \gamma c_{3w}(\overline{\rho v})_w = \gamma\left[\frac{M_3}{M_2}\,c_{2w}\exp\frac{\theta_w}{1+\beta\theta_w} - ac_{3w}\exp\frac{b_1\theta_w}{1+\beta\theta_w}\right], \tag{10}$$

$$-\frac{\lambda_w}{\lambda_e}\,\mathrm{Le}_w\sqrt{\frac{2\Delta}{\mathrm{Pr}_e}}\,(c'_{4\eta})_w + \gamma c_{4w}(\overline{\rho v})_w = 0, \quad f_w = -\frac{\gamma(\overline{\rho v})_w}{\sqrt{2\Delta\,\mathrm{Pr}_e}}\cdot\frac{\rho_w}{\rho_e}, \quad f'_\eta(0) = 0, \qquad (11),(12)$$

$$\theta_s(0, Y_s) = \theta_s(\tau, \infty) = \theta_{s0}. \tag{13}$$

In the numerical solution of this problem it was additionally assumed that the Prandtl and Lewis numbers are constants, while the dimensionless function l was taken as equal to unity. The kinetic constants for the homogeneous reaction were taken from [1], those for the heterogeneous reactions were taken from [2], and the initial temperature and taken as the characteristic temperature T_*.

The boundary problem (1)-(13) was solved by a difference system obtained on the basis of the iteration-interpolation method [3].

A series of calculations, in the course of which the velocity and temperature of the oncoming stream, the gas composition at the outer limit of the boundary layer, the thermokinetic constants of the homogeneous and heterogeneous chemical reactions, and the Prandtl and Lewis numbers were varied, was performed on a BÉSM-4 computer. In all the calculations we took the pressure as equal to 1 atm and the coefficient of thermal conductivity of the electrode carbon as $\lambda_s = 0.001$ cal/cm · sec · °K. With subsonic

TABLE 1. Effect of Chemical Nonequilibrium in the Boundary Layer on the Temperature of the Interface and the Ablation Rate

t, sec	0	0,2210	0,4421	0,6632	0,8843
$T_{w}f$, °K	1000	1130	1249	1383	1490
T_{w}, °K	1000	1130	1249	1385	1501
$10^2 (\rho v)_{w}f$	0,0156	0,0519	0,0957	0,1376	0,1726
$10^2 (\rho v)_{w}$, $\frac{g}{cm^2 \cdot sec}$	0,0156	0,0517	0,0955	0,1373	0,1687

flow over the vicinity of the frontal stagnation point of a hemispherical body $(du_e/dx)_{x=0} = \beta_x = 3/2 \cdot u_\infty/r_w$, while with supersonic flow over the body this value must be determined from the Newton equation [4].

Neglecting radiation, we will examine the flow of a "frozen" gas stream over the body.

A series of curves of $T_w(t)$ is given in Fig. 1. The first four curves have a point of inflection at $t = t_0$, separating the two modes of occurrence of the heterogeneous reactions: kinetic, in which the rate of the process is limited by the reaction rate, and diffusional, in which the rate of the process is limited by the rate of supply of the oxidant. In accordance with [5] we will call t_0 the heterogeneous ignition time. From a comparison of curves 1 and 2 it is seen that the ignition time increases considerably with an increase in the rate of supply of the oxidant, since the low temperature of the oxidant hinders the growth of the rate of the primary heterogeneous reaction. This mode of ignition, which was examined earlier in [5], is called self-ignition.

In addition to the mode of self-ignition, there is an ignition mode (see curves 3 and 4 in Fig. 1) in which an increase in the rate of supply of hot oxidant produces a decrease in the ignition time t_0.

Thus, for the ignition mode the hot stream of oxidant promotes an increase in the rate of the heterogeneous reaction $C + O_2 = CO_2$.

If the conditions for the occurrence of the heterogeneous exothermic reaction are extremely unfavorable – very low temperatures and a high velocity of the oncoming stream – then the diffusional mode of occurrence of the chemical reactions is not realized and cooling of the model occurs (see curve 5 of Fig. 1).

A qualitative difference between the modes of self-ignition and ignition follows from an analysis of the curves of Fig. 2, in which the ignition times t_0 are shown graphically as a function of β_x with an initial temperature of the body $T_* = 1000$°K for the two values $T_e = 900$°K and $T_e = 1500$°K (curves 1 and 2).

By analyzing the behavior of curve 2 of this figure one can postulate the existence of a temperature T_e of the external stream for which the ignition time t_0 will not depend on the velocity of the oncoming gas stream. This result agrees with the data of [5], where such a value of t_0 is found analytically by the method of direct coordinate expansion [6].

As the calculations showed, the ignition time t_0 in the ignition mode depends strongly on the oxygen concentration c_{2e}. The ignition time increases considerably with a decrease in the oxygen concentration, since the lowering of the O_2 concentration decreases the rate of the primary exothermic reaction and the rate of the secondary endothermic reaction increases simultaneously with an increase in the CO_2 concentration.

Simultaneously with the determination of $T_w(t)$ and the concentrations $c_{\alpha w}(t)$ of the components we calculated the ablation rates $(\rho v)_w$ at different times. It was established, in particular, that in the ignition mode $(\rho v)_w$ at a fixed time increases with an increase in the stream velocity.

Since volumetric chemical reactions were not taken into account in this series of calculations, the profiles of temperature and concentration in the boundary layer are monotonic functions of η for any times t. The question of the effect of the homogeneous chemical reaction on the heat- and mass-exchange characteristics was studied at the same time.

As the numerical calculations showed, in the presence of a homogeneous chemical reaction the surface temperature and the ablation rate $(\rho v)_w$ differ significantly from the corresponding values of these characteristics obtained for "frozen" flow. The results of numerical integration of the system of Eqs. (1)-(6) with the boundary and initial conditions (7)-(13), which confirm the remarks made above, are presented in

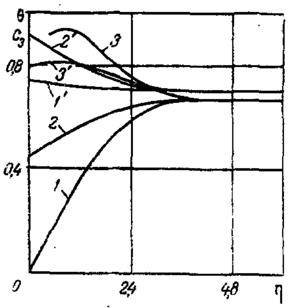

Fig. 3

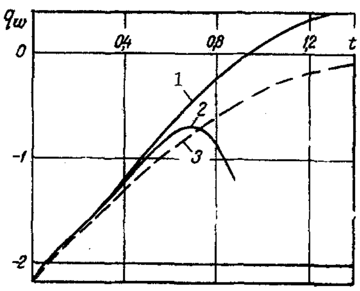

Fig. 4

Fig. 3. Profiles of dimensionless temperature θ (curves 1-3) and mass concentration of CO_2 (curves 1', 2', 3') in the boundary layer with $T_* = 1000°K$, $T_e = 1500°K$, $\beta_x = 1406.25$ sec^{-1}, $c_{2e} = 0.3$, and $c_{3e} = 0.7$ for different times: 1, 1') t = 0 sec; 2, 2') t = 0.685 sec; 3, 3') t = 1.625 sec.

Fig. 4. Heat flux q_w, cal/cm^2 · sec, from the gas phase as a function of the time t, sec with $T_* = 1000°K$, $T_e = 1500°K$, $\beta_x = 1876$ sec^{-1}, $c_{2e} = 0.3$, and $c_{3e} = 0.75$.

Table 1 for $\beta_x = 1875$ sec^{-1} and the previous values of the other parameters ($T_* = 1000°K$, $T_e = 1500°K$, $c_{2e} = 0.3$, $c_{3e} = 0.7$).

From the data of the table it follows that the ablation rate in the case of "frozen" flow is greater than the ablation rate for nonequilibrium flow. This fact is explained physically by the fact that because of the combustion of the carbon monoxide which forms, less oxygen and more carbon dioxide arrive at the interface.

The nature of the behavior of the distributions of temperature and concentrations within the boundary layer changes qualitatively in the case of nonequilibrium flow. Whereas for "frozen" flows the temperature and concentration profiles are monotonic curves, for nonequilibrium flow the temperature and CO_2 concentration profiles have a maximum for $t > t_0$, where t_0 is the ignition time. Graphs of the dimensionless temperature (curves 1, 2, 3) and mass concentration of CO_2 (curves 1', 2', 3') for different times are given in Fig. 3. It is seen that after a certain time, when a sufficient amount of CO, which serves as the initial product of the homogeneous reaction, is released as a result of the secondary heterogeneous reaction, a maximum of the temperature and CO_2 concentration is created near the interface.

The behavior of c_{3w} at the interface, which is connected with the mechanism of occurrence of heterogeneous chemical reactions, is easy to follow from Fig. 3. The primary reaction mainly proceeds at first because of the relation $E_1 < E_2$, as a result of which the CO_2 concentration at the surface increases. After arrival at the diffusional mode its rate hardly increases, and since the surface temperature becomes considerable the rate of the secondary heterogeneous reaction begins to increase, as a result of which the CO_2 concentration falls while the CO concentration grows.

The variation with time in the heat flux $-\lambda_w(\partial T/\partial Y)_w$ from the gas phase is shown in Fig. 4. Curve 1 corresponds to the case of a "frozen" boundary layer, while curve 2 corresponds to nonequilibrium flow in the boundary layer. The calculating parameters for the numerical integration were taken here as the same as the corresponding parameters of Table 1.

An analysis of the results of the numerical integration shows that for "frozen" flows the heat-exchange coefficient α, which is determined from the Newton law

$$q_w = \alpha (T_w - T_e) \tag{14}$$

when the heat flux q_w and the surface temperature are known, varies little with time. Thus, using the data of Table 1 and the values of the heat flux q_w corresponding to the points of curve 1 in Fig. 4 one can find $\alpha = 0.4452 \cdot 10^{-2}$ cal/cm^2 · sec · deg at the time t = 0 sec and $\alpha = 0.4318 \cdot 10^{-2}$ cal/cm^2 · sec · deg for t = 0.8843 sec. In connection with this, the solution of the problem (1)-(6) with the boundary and initial conditions (7)-(13) can be divided into two steps.

TABLE 2. Comparison of Theoretical and Experimental Values of Temperature within the Boundary Layer

y, mm	0,4	0,8	1,2	1,6	2,0
$\frac{\tilde{T}}{T}$	1,001	1,003	1,005	0,998	0,990

The first step consists in the determination of the fields of characteristics in the gas phase and of concentrations $c_{\alpha w}$ at the interface with T_w known. For this it is necessary to solve the system of Eqs. (1)-(5) in the gas phase with the corresponding boundary conditions (7), (9)-(12). By varying T_w parametrically and using the concept of the heat-exchange coefficient one can obtain approximating analytical equations for the heat flux from the gas phase and for the values $c_{\alpha w}(T_w)$.

The second step of the solution consists in the determination of the characteristics $T_w(t)$ and $(\rho\bar{v})_w(t)$, which are more important in practice, and the temperature distribution in the solid body. For this it is necessary to solve Eq. (6) for the heat conduction in the solid body with the boundary and initial conditions (8) and (13). In accomplishing the second step of the solution one must use approximating analytical equations for q_w and $c_{\alpha w}$.

At the same time, as follows from curve 2 of Fig. 4 the concept of the heat-exchange coefficient cannot be used in the case of chemically nonequilibrium flows in the boundary layer, since the heat-exchange coefficient loses physical meaning, becoming negative,† for example, for times $t \geq 0.8843$ sec. In fact, as follows from Table 1 and Eq. (14), at $t = 0.8843$ sec the temperature $T_w = 1501$°K and α changes sign and becomes equal to -1.2635 cal/cm$^2 \cdot$sec.

The interpretation of the coefficient α as a purely mathematical function of the surface temperature T_w and a number of other parameters, which can vary in the range from $+\infty$ to $-\infty$, is also inadvisable, since in this case great difficulties arise is the analytical approximation of the results obtained, leading to unjustified expenditures of machine time. Therefore one must solve the conjugate problem of heat and mass exchange.

With the flow of a "frozen" gas stream over a nonreacting solid body the behavior of the heat flux can be represented qualitatively by the dashed curve 3. As $t \to \infty$ the value $-\lambda_w \partial T/\partial Y \to 0$, i.e., with time the surface of the body assumes the temperature T_e of the oncoming gas stream through processes of convective heat transfer and heat conduction. In the case of a heterogeneous exothermic reaction the process of equalization of the surface temperature T_w and the temperature of the oncoming stream occurs considerably faster, and because of the high heat-up of the surface the heat flux can become positive (curve 1).

For chemically nonequilibrium flow in the boundary layer the variation in the heat flux with time has a nonmonotonic nature (see curve 2 of Fig. 4). In this case the heat input from the homogeneous chemical reaction begins to compete with the process of equalization of the temperatures of the body and the oncoming gas stream, and the heat flux to the body begins to decrease when there is considerable nonequilibrium in the gas phase. We note that the necessity of solving the conjugate problem of heat and mass exchange can be connected with the appearance of a maximum of the function $q_w(t)$ or a maximum of the function $\theta(\eta, \tau)$, which are determined by the degree of nonequilibrium of the chemical reaction in the gas phase. The degree of nonequilibrium of a homogeneous chemical reaction is determined by the Damkeller number, i.e., the ratio of the characteristic times of convective relaxation $t_M \sim 1/\beta_x$ and of the reaction t_{pi}.

It should be noted that when the inequality $t_M \ll t_{pi}$ in the gas phase is violated it is necessary to solve the nonsteady equations of heat and mass exchange.

In our case $t_M \approx 10^{-3}$ sec and $t_{pi} \approx 10^{-2}$ sec with $T_* = 1000$°K, i.e., the inequality $t_M \ll t_{pi}$ is satisfied. Besides this inequality, for the quasisteadiness of the processes in the gas phase it is necessary that the relaxation times t_i of the processes of molecular transfer and the reaction times t_{pi} in the gas phase be considerably less than the relaxation time t_s in the solid body. Using the numerical solutions found, one

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†A similar conclusion was drawn earlier in [7, 8] for one class of problems of convective heat exchange between an inert gas stream and an inert solid body.

can determine the displacement thicknesses of the thermal, dynamic, and diffusional boundary layers and then, using the thermal diffusivity, viscosity, and diffusion coefficients, estimate the characteristic times of the molecular transfer processes. It is not hard to show that $t_i \sim \delta^2/\nu$, where δ is the dynamic displacement thickness in Dorodnitsyn–Lees variables and ν is the kinematic viscosity coefficient. The estimates show that $t_i \approx 10^{-3}$ sec.

The time of thermal relaxation in the solid body, which we take as equal to the time of travel of the thermal wave to the center of a hemispherical model with a constant surface temperature, can be determined from [9]. Actually, this time is less than the relaxation time, since it does not include the time of formation of a constant temperature at the surface of the model. The relaxation time t_s is on the order of $10\text{-}10^2$ sec, and therefore, allowing for the estimates made above, one can assert that a quasisteady formulation of the problem is physically correct in the present case.

It is interesting to compare the theoretical data obtained above with certain experimental results [10]. Attention is attracted to the fact that temperature maxima within the boundary layer were also determined through thermocouple measurements [10]. At the same time, according to the theoretical results the temperature profile obtained experimentally will represent a monotonic curve when the temperatures T_e and T_w are low enough. The ratio $K = \tilde{T}/T$ in the case of steady combustion of the model is given in Table 2, where $\tilde{T} = T(y)$ is the temperature within the boundary layer, obtained experimentally in [10] with $T_e = 1200\,°K$, $c_{1e} = 0$, $c_{2e} = 0.22$, $c_{3e} = 0.02$, $c_{4e} = 0.76$, $u_\infty = 15$ cm/sec, and $r_w = 0.5$ cm (the model, made of electrode carbon, burns in a stream of heated air).

It is seen that good quantitative agreement between the theoretical and experimental results is observed in this case.

At higher values of T_e, when a temperature maximum appears, the difference between the theoretical and experimental temperatures (especially in the vicinity of the maximum) becomes more marked. This result is evidently due to the inaccuracy of the values used for the activation energy and the preexponent of the homogeneous reaction and by noncorrespondence between the mathematical model and nature (in this case, as follows from the form of the temperature curves presented in Fig. 11a of [10], the thickness of the boundary layer is comparable with the diameter of sphere over which the gas stream flows).

NOTATION

ξ, η	are the Dorodnitsyn–Lees variables;
ρ	is the density;
$l = \mu\rho/\mu_e\rho_e$	is a dimensionless parameter;
μ	is the coefficient of viscosity of mixture;
ν	is the coefficient of kinematic viscosity of mixture;
D	is the binary diffusion coefficient;
$f_w = (\rho v)_w/\sqrt{2\beta_x\rho_e\mu_e}$	is the dimensionless stream function;
$\beta_x = (du_e/dx)_{x=0}$	is the dimensional parameter connected with the characteristic mechanical time;
M_α	is the molecular weight of component α;
c_α	is the mass concentration of component α;
$\theta = (T-T_*)E_1/RT_*^2$	is the dimensionless temperature;
$E, q, k, E_1, q_1, k_1, E_2, q_2, k_2$	are the activation energy, heat of chemical reaction, and rate constant of chemical reaction for the homogeneous and the primary and secondary heterogeneous reactions, respectively;
p	is the pressure;
$\mathrm{Dam} = (T_*^{-3.25}E_1qk/2\beta_x pc_p) \cdot \exp(E/RT_*)$	is the Damkeller number;
c_p	is the specific heat capacity of mixture at constant pressure;
$\mathrm{Pr} = \mu c_p/\lambda$	is the Prandtl number;
$\mathrm{Sc} = \mu/\rho D$	is the Schmidt number;
$\mathrm{Le} = \mathrm{Pr}/\mathrm{Sc}$	is the Lewis number;
λ	is the coefficient of thermal conductivity of mixture;
$\beta = RT_*/E_1$	is a dimensionless parameter;
R	is the universal gas constant;
$\gamma = c_pRT_*^2/q_1E_1$	is a dimensionless parameter;

$b = E/E_1$, $b_1 = E_2/E_1$	are dimensionless parameters;
$\Delta = \beta_x t_*$	is the parameter characterizing the ratio of the characteristic "chemical" time for the primary heterogeneous reaction to the characteristic mechanical time;
$t_* = r_*^2 \rho_e c_{pe}/\lambda_e$	is the characteristic chemical time;
$\tau = t/t_*$	is the dimensionless time coordinate;
$r_* = (\lambda_e R T_*^2/\rho_e E_1 q k_1) \exp E_1/RT_*$	is the characteristic "chemical" size;
$Y_s = (y/r_*)\sqrt{\pi_\varkappa}$	is the dimensionless coordinate in solid body;
$\pi_\varkappa = \lambda_e \rho_s c_{ps}/\lambda_s \rho_e c_{pe}$	is a dimensionless parameter;
$K_\varepsilon = \sqrt{\lambda_s \rho_s c_{ps}/\lambda_e \rho_e c_{pe}}$	is the dimensionless coefficient of thermal activity of solid body;
$(\overline{\rho v})_w = \pi_\varkappa [(M_3/M_2) - 1 c_{2w} \cdot \exp[\theta_w/(1 + \beta\theta_w)] + [2(M_1/M_2) - 1] a c_{3w} \exp[b_1\theta_w/(1 + \beta\theta_w)]$	is the dimensionless ablation rate;
$a = (k_2/k_1)\exp[(E_1 - E_2)/RT_*]$	is a dimensionless parameter;
$\pi_\sigma = \varepsilon\delta T_*^2 r_* E_1/\lambda_e R$	is the dimensionless parameter characterizing the radiant heat flux;
T_*	is the initial temperature of model in °K.

Indices

w and *	are assigned to parameters at $\eta = Y_s = 0$ and to characteristic values, respectively;
e	pertains to values at the outer limit of the boundary layer;
s	pertains to parameters of the solid phase;
f	pertains to parameters of "frozen" flow.

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