CONCERNING HETEROGENEOUS COMBUSTION OF AEROSOL PARTICLES IN A LASER-RADIATION FIELD

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As shown in [1], electromagnetic radiation can influence substantially the heterogeneous combustion of particles (e.g., coal) suspended in a gaseous medium. It is of interest in this connection to develop a quantitative theory of the combustion of aerosol particles at large temperature difference between the particle surface and the surrounding medium. This calls already for taking into account the dependence of the transport coefficients (of the thermal conductivity $\varkappa$ and of the diffusion D) on the temperature. It should be noted here that heterogeneous combustion of aerosol particles cannot always be described by a power-law dependence of $\varkappa$ and D on the temperature T of the gas mixture (such as, e.g., $\varkappa = \varkappa_0 (T/T_\infty)^{1/2}$ and $D = D_0 (T/T_\infty)^{3/2}$ [1]). The value for air calculated from the formula $\varkappa = \varkappa_0 (T/T_\infty)^{1/2}$ at $T = 3000^\circ K$ ($T_\infty = 300^\circ K$) is six times smaller than the real value.

No restrictions are imposed in the present description of the combustion of spherical particles of radius R on the type of the dependence of the coefficients $\varkappa$ and D on T. The theory is constructed in a quasistationary approximation for a spherically symmetric model of the combustion. Particle combustion was considered in a three-component gas mixture consisting of the molecules of the oxidant (first component), of the molecules of some oxide of the combustible substance (second component), and molecules of an inert gas (third component). The following scheme was assumed here for the reaction of the oxidation of the molecules of the material of particle A_4 by the oxidant molecules A_1: $\nu_1 A_1 + \nu_4 A_4 = \nu_2 A_2$, where the symbols A_1, A_2, A_4 designate atoms or molecules. The distribution of the temperature T and of the concentrations n_1, n_2 and n_3 of the oxidant oxide, and inert gas, respectively, in the vicinity of the particle can be described with the aid of the system [2] of Eqs. (1) subject to boundary conditions (2) and (3):

$$\frac{dc_j}{dr} = \frac{1}{n} \sum_{\ell=1}^{3} \frac{1}{D_{j\ell}} (J_\ell c_j - J_j c_\ell), \quad \frac{d}{dr} r^2 \left[\varkappa \frac{dT}{dr} - \sum_{\ell=1}^{3} \gamma_\ell k T J_\ell \right] = 0, \tag{1}$$

$$J_1 \big|_{r=R} = -nhc_1 \big|_{r=R}, \qquad T \big|_{r=R} = T_s \tag{2}$$

$$c_1 \big|_{r\to\infty} = c_{1\infty}, \quad c_2 \big|_{r\to\infty} = c_{2\infty}, \quad c_3 \big|_{r\to\infty} = c_{3\infty}, \quad T \big|_{r\to\infty} = T_\infty, \tag{3}$$

where $c_j = n_j/n$, $n = n_1 + n_2 + n_3$; $D_{j\ell}$ are the coefficients of binary diffusion; J_ℓ, flux density of the molecules of species ℓ; γ_ℓ, heat capacity at constant pressure per molecule

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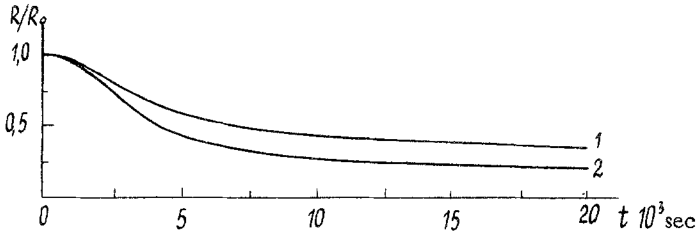

Fig. 1

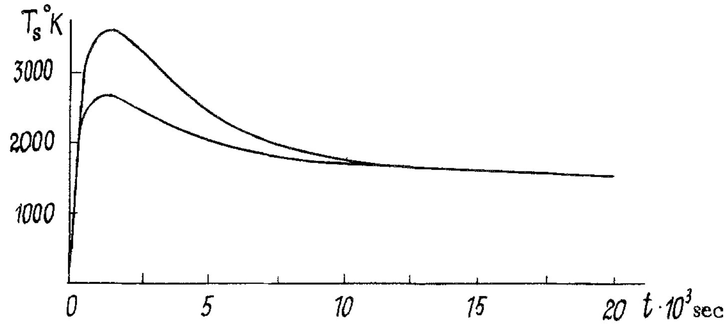

Fig. 2

of species ℓ [2]; κ, Boltzmann's constant; $\varkappa$, thermal conductivity coefficient; h, reaction-rate constant, depending on the particle surface temperature T_s. The integration in (1) was carried out at $D_{j\ell}=D^\circ_{j\ell}f(\theta)$, $D^\circ_{j\ell}=\text{const}$, $\theta=T/T_\infty$. As a result we obtained the following expressions that describe the distributions of C_j and T:

$$C_1=\frac{1}{\delta_2}(1-e^{\delta_2\xi})+\left(1-\frac{D^\circ_{12}}{D^\circ_{31}}\right)\frac{[e^{\delta_1\xi}-e^{\delta_2\xi}]}{(\delta_1-\delta_2)}C_{3\infty}+C_{1\infty}e^{\delta_2\xi}, \tag{4}$$

$$C_3=C_{3\infty}e^{\delta_1\xi}, \quad C_2=[1-C_1-C_3], \tag{5}$$

$$\frac{1}{y}=4\pi RT_\infty\int_1^\theta\frac{\varkappa d\theta}{[Q_T-Q_1\kappa T_\infty\theta(\gamma_1-\frac{\nu_2}{\nu_1}\gamma_2)]} \tag{6}$$

In Eqs. (4)-(6) we put $\xi=\frac{Q_1}{4\pi RD^\circ_{12}}\int_\infty^y\frac{dy}{ny^2f(\theta)}\equiv\frac{Q_1T_\infty}{D^\circ_{12}}\int_\theta^1\frac{\varkappa d\theta}{nf(\theta)[Q_T-Q_1\kappa T_\infty\theta(\gamma_1-\frac{\nu_2}{\nu_1}\gamma_2)]}$; $y=\frac{r}{R}$, r is the radial coordinate; Q_1 and Q_T, algebraic values of, respectively, the total fluxes of the oxidant molecules and of the heat; ν_1 and ν_2, stoichiometric coefficients of the reaction; $\delta_1=[(D^\circ_{12}/D^\circ_{13})-(\nu_2D^\circ_{12}/\nu_1D^\circ_{23})]$, $\delta_2=1-\frac{\nu_2}{\nu_1}$. The values of Q_1 and Q_T and of the temperature T_s are then obtained in the course of solving the system of equations

$$Q_1=-4\pi R^2n_sC_{1s}h, \quad 1=4\pi RT_\infty\int_1^{\theta_s}\frac{\varkappa d\theta}{[Q_T-Q_1\kappa T_\infty\theta(\gamma_1-\frac{\nu_2}{\nu_1}\gamma_2)]}, \tag{7}$$

$$\frac{4}{3}\pi\rho_L\beta_{PL}R^3\frac{dT_s}{dt}=Q_e-Q_T-q_1m_1Q_1-4\pi R^2\sigma\varepsilon(T_s^4-T_\infty^4), \tag{8}$$

$$\frac{4}{3}\pi\frac{d}{dt}(\rho_LR^3)=\frac{\nu_4}{\nu_1}m_4Q_1, \tag{9}$$

where $n_s = n|_{y=1}$, $c_{1s} = c_1|_{y=1}$, $\theta_s = T_s/T_\infty$; ρ_i is the density of the particle material; β_{pi}, its specific heat at constant pressure; Q_e, heat released per unit time inside the particle; m_1 and m_4, masses of the oxidant and particle-material molecules; q_1, thermal effect of the reaction; σ, Stefan–Boltzmann constant; and ε, integral degree of blackness of the particle. Equations (7) were obtained from (2); Eqs. (8) and (9) are the thermal-energy and particle-mass conservation laws, and t is the time. At a given value of θ_s the quantities Q_1 and Q_T are determined in the course of the solution of Eqs. (7). The densities c_1, c_2 and c_3, contained in $\varkappa$, are calculated from (4) and (5). It is expedient in this case to determine ξ by transforming to the independent variable θ.

System (7)-(9) is simplest to solve in those cases when $\varkappa$ depends weakly on c_1, c_2, and c_3, for in this case the variables c_1, c_2 and c_3 are functions of θ only.

In the course of solving (7)-(9) one can find the dependences of T_s and R on the time t. Numerical estimates with the aid of (7)-(9) have shown that the values of T_s and the combustion time depend substantially on the form of the dependence of the transport coefficients on θ. This is clearly seen from the form of the curves in Figs. 1 and 2, which show respectively plots of R/R_0 and T_s against t for coal particles with initial radius $R_0 = 5$ μm, burning in air with $c_1 = c_0 = 0.21$, $p = 1$ atm, $T = 300°$ at a radiation intensity $I = 2 \cdot 10^8$ W/m²·sec at an absorption factor $K_n = 1$ and $Q_e = \pi R^2 I K_n$. Curves 1 in Figs. 1 and 2 were plotted for real dependences of the transport coefficients on θ, taken from [3], while curves 2 were plotted at $\varkappa = \varkappa_0 \theta^{1/2}$ and $D_{jl} = D_{jl}^0 \theta^{3/2}$. The calculations were carried out at $\rho_i = 2250$ kg/m³, $D_{12}^0 = 1.75 \cdot 10^{-5}$ m²/sec, $D_{13}^0 = 1.82 \cdot 10^{-5}$ m²/sec, $D_{23}^0 = 1.75 \cdot 10^{-5}$ m²/sec, $h = z \exp[-E_i/RT_s]^{13}$, $z = 5.25 \cdot 10^4$ m/sec, $E_i = 1.25 \cdot 10^5$ J/mole. The combustion reaction $2C + O_2 = 2CO$ was used in the calculations.

LITERATURE CITED

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