INFLUENCE OF NATURAL AND FORCED CONVECTION ON THE CHARACTERISTICS OF HETEROGENEOUS COMBUSTION OF A CARBON PARTICLE

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The little-studied problem of the effect of natural and forced convection on the stationary (combustion) and critical (ignition and extinction) high-temperature states of a carbon particle with account for radiative heat exchange with the cold walls of the processing setup is considered. The effect of molecular and convective heat and mass exchange of a carbon particle with a gas on the critical diameter of the particle \( d_c \) at which the particle is spontaneously extinguished (a jumpwise transition from combustion to oxidation) is analyzed.

Chemical conversions of carbon particles in torch or circulating fluidized bed furnaces occur with intense heat and mass exchange (HME) with a gas phase. The role of convective heat and mass exchange in the processes of heterogeneous ignition, combustion, and extinction of carbon particles has virtually not been revealed in the specialized and educational literature. The rate of convective HME can increase and decrease with change in the diameter and relative velocity of the particle. In [1] the existence of upper and lower limits of the size of motionless carbon particles that bound regions of stationary heterogeneous combustion of them is shown. It is found that the upper limits are related to the heat exchange of the particle with the cold walls of the processing setup.

In what follows, the effect of the relative velocity on the stationary and critical modes of heat and mass exchange of a moving particle is studied. With account for the parallel heterogeneous chemical reactions \( C + O_2 \rightarrow CO_2 \) (I) and \( 2C + O_2 \rightarrow 2CO \) (II) for \( Bi \ll 1 \) the equation of heat balance of a particle has the form

\[
\frac{1}{6} c_1 \rho_1 d \frac{dT_1}{dt} = q_{\text{ch}} - q_{m.c} - q_r, \quad T_1 (t = 0) = T_{\text{beg}},
\]

where

\[
q_{\text{ch}} = \left( \sum_{i=1}^{2} k_i Q_i \right) \rho_2 n_{\text{ox}} \left( \frac{\sum_{i=1}^{2} k_i}{1 + \beta} + 1 \right)^{-1}, \quad k_i = k_{0i} \exp \left( - \frac{E_i}{RT_1} \right);
\]

\[
\beta = D \frac{\text{Nu}}{d} \quad D = \frac{\lambda_2}{(c_2 \rho_2)};
\]

\[
\text{Nu} = 2 + b \sqrt{\text{Re} \Pr^{1/3}}, \quad b = 0.55 \quad \text{[2]}, \quad \text{Re} = Ud/v_2, \quad v_2 = \frac{D}{\Pr} D;
\]

\[
q_{m.c} = \alpha (T_1 - T_2); \quad \alpha = \frac{\lambda_2 \text{Nu}}{d}; \quad q_r = \varepsilon \sigma (T_1^4 - T_w^4).
\]

The particle diameter \( d \) (the particle is taken to be spherical) decreases with time as a result of chemical conversions whose rate depends on the mass transfer of the oxidant to the particle surface:

Fig. 1. Time dependences of $T_1$, $d$, $dT_1/dt$, $W_C$, $U$, $k$, and $\beta$ for a particle with $d_{beg} = 505 \, \mu m$, $U_{beg} = 11 \, m/sec$, $T_2 = 1400 \, K$, $T_w = 500 \, K$: 1) $F_g \neq 0$, 2) 0. $T_1$, $K$; $d$, $\mu m$; $dT_1/dt$, $K/sec$; $W_C$, $kg/(m^2 \cdot sec)$; $U$, $k$, $\beta$, $m/sec$; $t$, sec.

\[
\frac{d (d)}{dt} = - \frac{2 \rho_2}{\rho_1} \left( \sum_{i=1}^{2} k_i \Omega_i \right) n_{ox} \left( \frac{2 \sum_{i=1}^{2} k_i}{\beta} + 1 \right)^{-1}, \quad d (t=0) = d_{beg}.
\]

The relative velocity of the particle $U$ is found from the equation of motion

\[
\frac{1}{6} \pi d^3 \rho_1 \frac{dU}{dt} = F_g - F_{fl} - F_{fr}
\]

or

\[
\rho_1 \frac{dU}{dt} = (\rho_1 - \rho_2) g - \frac{3}{4d} \psi \rho_2 U^2, \quad U (t = 0) = U_{beg},
\]

where $F_g$, $F_{fl}$, $F_{fr}$ are the force of gravity, the Archimedes force, and the force of friction, respectively; $U_{beg}$ is the initial velocity of the particle; the coefficient of head resistance of the particle $\psi$ depends on the Reynolds number, and within the range $1 < Re < 400$ it is found by the Klyachko formula [3]

\[
\psi = \frac{24}{\text{Re}} + \frac{4}{\sqrt{\text{Re}}}
\]

Numerical solution of Eqs. (1)-(3) with account for (4) and their analysis allow one to find the laws governing the occurrence of stationary high- and low-temperature states as a function of the velocity of motion and the diameter of the particle. The calculations were conducted for the following parameters: $E_1 = 140.03 \, kJ/mole$; $E_2 = 154 \, kJ/mole$; $k_{d1} = 45,000 \, m/sec$; $k_{d2} = 130,000 \, m/sec$; $Q_1 = 10,125 \, kJ/(kg \, O_2)$; $Q_2 = 6843.75 \, kJ/(kg \, O_2)$; $n_{ox} = 0.23$; $\varepsilon = 0.78$ [3]. The study of the stability of the stationary modes of HME ($dT_1/dt = 0$) makes it possible to determine the critical values of the velocity of motion of a particle and its diameter (and, correspondingly, $\alpha_{cr}$ and $\beta_{cr}$), which characterize transitions from stationary low-temperature to high-temperature states and conversely.

Figure 1 presents time dependences of the temperature (a), particle diameter (b), derivative $dT_1/dt$ (c), rate of chemical conversion of a particle with respect to carbon $W_C = -(1/2)\rho_1 d(d)/dt$ (d), relative velocity of particle motion (e), and rate constants of the chemical reactions and the coefficient of mass transfer (f) for two