NUMERICAL MODELING OF LIGHTING PROCESS IN PULVERIZED-COAL BURNER OF A BOILER UNIT BY THE LOW-TEMPERATURE PLASMA JET

Hranislav MILOSHEVICH and Alexander D. RYCHKOV
Institute of Computational Technologies, Siberian Branch of Russian Academy of Sciences
pr. Lavrentjeva 6, Novosibirsk 630090, RUSSIA

ABSTRACT
We numerically model the process of aeromixture ignition in a pulverized-coal burner by a central axysymmetric jet of air that is heated in an electrical arc plasma generator up to ~ 5000 K. Our aim is to investigate the process of coal particle ignition in the flow and establish the conditions under which the independent combustion of pulverized-coal mixture occurs. The results obtained allow us to show the important role of radiation heat transfer in initiating the combustion process of solid fuel particles.

NOMENCLATURE
\( \rho \) density
\( \rho \) pressure
\( \mu \) dynamic viscosity
\( \vec{U} \) vector of averaged gas velocity
\( \vec{u} \) vector of particles velocity
\( H \) enthalpy of gas
\( iC \) mass fraction of \( i \)-th species
\( iM \) molecular weight of \( i \)-th species

INTRODUCTION
One of the most interesting examples of the application of plasma technologies in boiler units is the use of a low-temperature plasma jet when lighting the boiler units at thermal power stations (TPS) and the stabilization of the combustion of pulverized-coal torch (Zhukov et al., 1996). This allows us to give up fuel oil or natural gas, which are generally used for these purposes, automate the lighting process, increase the completeness of solid fuel combustion, and decrease the level of noxious gas escaping into the atmosphere, i.e. allows us to considerably improve the economic and ecological characteristics of TPS. At present the full-scale experiments on the plasma lighting of pulverized-coal fired boilers are made at Gasinozersk TPS in Russia and at several TPS in Mongolia and China. The industrial development of this new technology is under way. However, many problems associated with a deep understanding of the peculiarities of physicochemical processes that take place in the interaction of such a plasma jet with a pulverized-coal flow still remain unsolved and invite further theoretical and experimental investigations.

In this paper we consider the numerical modeling of the process of aeromixture ignition in a pulverized-coal burner by the central axisymmetric jet of a low-temperature air plasma. The main aim of this modeling is to study the process of ignition of the coal particles in the flow and establish the conditions under which the independent combustion of pulverized-coal mixture occurs.

MODEL DESCRIPTION
Figure 1 shows the scheme of flow in a pulverized-coal burner that is a tube (muffle).

The air heated in an electric arc plasma generator to 5000K is supplied through the central part of the tube via the mouthpiece. The polydisperse pulverized-coal flow with weight content of solid fuel, which is typical for the pulverized-coal burners at TPS, is supplied through peripheral part of the tube. The jet flow and the peripheral low-speed two-phase flow are assumed to be axisymmetric and turbulent. We take into account the force and thermal interactions between a carrier gas and particles as well as all the basic stages of the process of ignition of the pulverized-coal particles, including the release of volatile matter and its combustion, ignition of coke residue and its combustion. When describing these processes we use the model of a coal particle with a durable ash frame (Volkov et al., 1980). According to this model when a particle is burning, its size does not change, only its composition changes (and hence its specific weight). According to the model the density of the particle \( \rho_i \) is represented by the formula \( \rho_i = \rho_0 (C + V + A) \), where \( C, V, A \) are the fractions of total mass of carbon, volatile matter and ash, respectively; \( \rho_0 \) is the density of the starting fuel. The volatile matter is assumed to contain hydrocarbons, water, and carbon dioxide: \( V = \{C_xH_y, H_2O, CO_2\} \). In the gaseous phase we take into account the nonequilibrium chemical dissociation reactions and exchange reactions, which take place in a low-temperature plasma (Ginzburg, 1975):

\[ O_2 \leftrightarrow O + O \quad N_2 \leftrightarrow N + N \quad NO \leftrightarrow N + O \]
\[ O_2 + N \leftrightarrow NO \leftrightarrow O + N \quad N_2 + O \leftrightarrow NO + N \]
\[ N_2 + O_2 \leftrightarrow NO + NO \]
Their rates are determined by the Arrhenius law. We also take into account the generalized combustion reaction of hydrocarbons:

\[
C_{n}H_{m} + (n + \frac{m}{4})[\alpha O_{2} + 2(1-\alpha)O] \rightarrow nCO_{2} + \frac{m}{4}H_{2}O
\]

where \(\alpha\) is the relative fraction of the molecular oxygen in the "generalized" oxidizer, which consists of a molecular and atomic oxygen mixture. The limiting stage in the combustion process is assumed to be the turbulent mixing that is described by the eddy breakup model (Magnussen and Hjertager, 1976). In this case, the mass combustion rate of \(C_{n}H_{m}\) is determined by formula

\[
J_{C_{n}H_{m}} = \min \{\rho C_{v} C_{n}H_{m} \varepsilon/k, \rho C_{v} C_{O_{2}} \varepsilon/k, \rho C_{H_{2}O} + C_{CO_{2}}/(1 + s) \varepsilon/k\}
\]

where \(s = (n + m/4) M_{O_{2}} / M_{C_{n}H_{m}}\) is the stoichiometric coefficient and \(A_{1}, A_{2}\) are empirical constants. In the case under study we assume that the carbon combustion occurs when there is an excess oxidant, and this process proceeds by the scheme of a one-stage reaction:

\[
C + [\alpha O_{2} + 2(1-\alpha)O] \rightarrow CO_{2}
\]

A characteristic feature of the flow considered is that near the nozzle outlet section there is a region free of particles. As the particles move, they gradually get into this region due to the mechanism of turbulent diffusion. At some distance from the section they can even intersect the axis of symmetry, which involves certain difficulties when describing their motion in the framework of a continuum approach. Therefore in this work we consider the motion of particles by the trajectory method of tracking particles, which was proposed by Crowe (1968). The effect of turbulent fluctuations in a carrier gas on the motion of particles is taken into account by the method of random walks (Mostafa and et al., 1989). Note that a particle track implies a 'packet' of particles of the same size, which move along a single trajectory. The particles get into the region of plasma jet mixing with the wake flow, where the flow is nearly stratified. Therefore in addition to the aerodynamic drag we take into account the Saffman force as well as the rotation of particles which are assumed to be spherical. We consider both the convective and radiative heat exchange between the gas and the particles. At this stage of investigation the radiative heat transfer is determined by the simplest method, viz. by the average radiation temperature of the medium, which takes into account the thermal radiation of both the plasma jet and the particles.

We calculate the release of the volatile matter by a first-order reaction, using the one-component scheme. The rate of the reaction is determined by a diffusive kinetic relation that takes into account both the process kinetics described by Arrhenius law and the diffusion resistance when the volatile matter passes through the fuel particle mass (Volkov et al., 1994). When calculating the carbon combustion (coke residue) we use the semiempirical relation given by (Babii and Kuvaye, 1986), which also takes into account the diffusive kinetic character of this process.

\[\text{Mathematical model}\]

The system of equations of particle motion, written for the trajectory of the \(i\)-th particle, has the form

\[
\frac{du_{i}}{dt} = C_{Ri} (u - u_{i}) - \frac{3}{4} \frac{\rho}{\rho_{hi}} (v - v_{i})(\omega_{i} - \frac{1}{2} - \frac{\partial U}{\partial y})\]

(1)

\[
\frac{dv_{i}}{dt} = C_{Ri} (v - v_{i}) + \frac{3}{4} \frac{\rho}{\rho_{hi}} (u - u_{i})(\omega_{i} - \frac{1}{2} - \frac{\partial U}{\partial y}) + \frac{9.69}{\pi \rho_{hi} d_{i}} \text{sign} \left( \frac{\partial U}{\partial y} \right) (u - u_{i}) \times \sqrt{\frac{\partial U}{\partial y}}
\]

(2)

\[
\frac{d\omega_{i}}{dt} = C_{mi} \left[ \frac{1}{2} \frac{\partial U}{\partial y} - \omega_{i} \right]
\]

(3)

\[
\frac{dm_{hi}}{dt} = -\beta A_{\varepsilon} \exp(-E_{\varepsilon}/RT_{j}) m_{hi}/(1 + A_{\varepsilon} \exp(-E_{\varepsilon}/RT_{j}) D_{i}) = \alpha_{j}
\]

(4)

\[
\frac{dm_{wi}}{dt} = -A_{\alpha} \exp(-E_{\alpha}/RT_{i}) m_{wi}/1 + 1/6 A_{\alpha} \exp(-E_{\alpha}/RT_{i}) D_{i} = \alpha_{j}
\]

(5)

\[
c_{mi} \frac{dT}{dt} = \frac{1}{\rho_{hi} d_{i}} \left[ \frac{1}{2} \frac{\partial U}{\partial y} - \omega_{i} \right] \right] + q \frac{J_{\alpha}}{q_{J_{\alpha}} - q_{J_{\alpha}}} \equiv \theta_{i}
\]

(6)

\[
C_{Ri} = \frac{18}{\mu} \frac{\rho_{hi}}{d_{i}} \left( 1 + 0.179 \frac{Re_{p_{1}}}{Re_{p_{2}}} + 0.013 (Re_{p}) \right),
\]

\[
C_{wi} = \frac{60 \mu}{\rho_{hi} d_{i}^{2}} \left\{ \left( \frac{\rho}{\rho_{hi}} \right)^{1/2} \frac{dU}{dU - \dot{u}} \right\}
\]

where \(m_{i}, m_{wi}, m_{wi}\) are the mass of particle and the masses of carbon and volatile matter in it; \(\rho_{hi}, d_{i}\) are the density of a particle and its diameter; \(q_{J_{\alpha}}, q_{J_{\alpha}}\) are the heat release of the combustion reaction of the coke residue and volatile matter accordingly; \(\beta\) is the efficient stoichiometric coefficient; \(C_{Ri}, \alpha_{i}\) are the drag coefficient and the heat transfer coefficient; \(E_{\varepsilon}, \sigma\) are the emissivity factor of the particle and the Stefan-Boltzmann constant; \(T_{\alpha}\) is the section-averaged radiation temperature. The vector \(\dot{u}\) is determined as a random quantity with Gaussian distribution and mean square deviation equal to \(2/3 k\) (Mostafa et al., 1989).

In order to describe the motion of a carrier gas we use Reynolds averaged system of Navier-Stokes equations, which is closed by the standard \(k - \varepsilon\) model of turbulence, in which the interphase interactions are taken into account for both averaged and fluctuating motions. The system of these equations for the case of an axisymmetric flow is written as (summation is performed by recurring indices, \(\mu, k = 1, 2\)):
\[
\frac{\partial}{\partial x_k} y p U_k = y J \tag{7}
\]

\[
\frac{\partial}{\partial x_k} y p U_i + \frac{\partial}{\partial x_k} y p = \frac{\partial}{\partial x_k} y [\mu \tau_k - \rho < u_i u_k^* >] + \frac{\partial}{\partial x_k} y [\tau_k - \rho < h u_k^* > + \mu \tau_k] \tag{8}
\]

\[
\frac{\partial}{\partial x_k} y p H U_k = \frac{\partial}{\partial x_k} y [\lambda + \frac{\partial T}{\partial x_k}] - \rho < h u_k^* > + \mu [\tau_k - \rho < u_i u_k^* >] + \frac{\partial}{\partial x_k} y [\tau_k - \rho < h u_k^* > + \mu [\tau_k - \rho < u_i u_k^* >]\tag{9}
\]

\[
\frac{\partial}{\partial x_k} y p C U_i = \frac{\partial}{\partial x_k} y [(\rho D_i + \mu_i) \frac{\partial C_i}{\partial x_k}] + y J_i \tag{10}
\]

\[
\frac{\partial}{\partial x_k} y p k U_i = \frac{\partial}{\partial x_k} y [(u + \mu_i) \frac{\partial k}{\partial x_k}] - y [\rho < u_i u_i^* >] \times \frac{\partial U_j}{\partial x_k} + \rho e + k \psi \tag{11}
\]

\[
\frac{\partial}{\partial x_k} y p e U_i = \frac{\partial}{\partial x_k} y [\mu_i + \frac{\partial e}{\partial x_k}] - y [C_i \rho p < u_i u_i^* >] \times \frac{\partial U_j}{\partial x_k} + C_i \rho \frac{\partial^2}{\partial x_k} + C_i \psi \tag{12}
\]

\[
p = \rho R_0 \sum_{i=1}^{n_p} C_i / M_i \tag{13}
\]

\[
\rho < u_i u_i^* >= 2 \left[ \frac{\partial p \delta_k - \mu_i \tau_k}{\partial x_k} + \frac{\partial H}{\partial x_k} \right] \tag{14}
\]

\[
\rho < h u_i^* >= \frac{\partial \mu_i}{\partial T} \tag{15}
\]

\[
J = n_p << q_i >> + << q_i^* >> \tag{16}
\]

where \( i = \{ O, O_2, N, N_2, NO, C_i H_m, CO_2, H_2O \} \).

The terms in double broken brackets take into account the interphase interactions. We determine them by the space-time averaging of the values in the brackets over the segments of the trajectories of the particle tracks that cross the boundaries of a calculated cell of the difference grid \( V_{m,n} \):

\[
n_p = \sum_{k=1}^{n_p} \eta_k \tau_k \tag{17}
\]

\[
<< \varphi >><><\sum_{k=1}^{n_p} \frac{\eta_k}{\tau_k} dt \tag{18}
\]

\[
<< \varphi >><><\sum_{k=1}^{n_p} \frac{\xi_k}{\tau_k} \tag{19}
\]

where \( \eta_k \) is the number of particles in the 'packet' of particles along the \( k \)-th trajectory, which are determined by the conditions at the initial section, \( \varphi \) is any of \( q_i, q_i^*, F_i, Q \), etc. in (8), (9).

For the system of equations (1) - (6) only the initial conditions at the burner inlet section are given. The moving particles can be reflected from the wall of the tube and intersect the axis of symmetry. The boundary conditions, which are given for the system (7) - (13), are the following: a no-slip condition on the tube wall, symmetry conditions along the axis, and 'mild' boundary conditions at the outlet section. They are typical of internal turbulent flows. We assume that the developed turbulent flow with profile of the longitudinal component of the velocity vector occurs at the inlet section and the profile varies near the walls by 1/7 law.

In order to solve the system of equations (1) - (6), which belongs to the class of 'stiff' systems, we use the implicit A-stable difference scheme of second-order accuracy (Rychkov, 1980). We solve the system (7) - (13) by the semiimplicit difference scheme of the Patankar method until the solution is stabilized (Patankar, 1980). We take into account the interphase interactions by iterations when successively solving these systems of equations (Rychkov, 1980).

**RESULTS**

We calculated the lighting process for the case of a polyparticle dispersed pulverized-coal flow (particles of three sizes were used) at the value of the basic parameters:

\( T_0 = 5000 \text{ K}, T_i = 3000 \text{ K}, R_0 = 0.015 \text{ m} \),

\( d_1 = 8 \times 10^{-4} \text{ m}, \ d_2 = 10^{-4} \text{ m} \),

\( d_3 = 1.2 \times 10^{-4} \text{ m}, \ w_{p1} = 0.3, \ w_{p2} = 0.5, \ w_{p3} = 0.2 \),

\( U_0 = 300 \text{ m/s}, \ U_i = 10 \text{ m/s}, \ R_a = 0.15 \text{ m} \).

Here \( T_0, T_i \) are the temperatures of the jet and the wake flow at the inlet section; \( R_a, R_a \) are the radiuses of the nozzle and the muffle, respectively; \( d_2, w_{p1} \) are the diameters of the particle and the relative weight fraction of each size. We did not take into account the force and thermal interactions between the particles of various sizes. The mass composition of the fuel and the empirical coefficients in equations (1) - (3) were taken to be the same as in those in (Volkov et al., 1980).

**Figure 2:** Isotherms of a carrier gas in the case of two-phase (a) and one-phase (b) flows.

Figure 2 (hereafter all the linear dimensions are referred to the radius of the nozzle outlet jet section) shows the isotherms of the flow field for the case of a two-phase flow (Figure 2a) and for the case of a pure gas flow (Figure 2b, isolines are plotted with step \( \Delta T = 250 \text{ K} \)). As seen in Figure 2, near the nozzle section the temperature of the jet due to heat transfer decreases faster. However, as the volatile matter are released and the coke particles and the volatile matter burn, the temperature in the flow field turns out to be higher than that in the pure gas flow. It is interesting to note that the coal particles in the flow outside the plasma jet ignite near the wall of the tube (muffle).
The analysis of the isolines leads to the conclusion that in the lighting scheme under study practically all atomic oxygen is consumed in the recombination reactions near the nozzle section in the zone free of particles. Its effect on the ignition process of the fuel particles turns out to be insignificant. It seems likely that its role will be more significant if part of the pulverized-coal flow is supplied via the nozzle, i.e. if it passes through the region of the low-temperature plasma flow.

CONCLUSION

The results of numerical modeling have shown an essential role of a radiative heat transfer in ignition process of coal particles in a pulverized-coal burner. Therefore it is possible to assume that the intensification of a radiant emittance of a high-temperature jet will allow an increase in the efficiency of ignition. For example it would be possible to feed a part of a pulverized-coal mixture through the nozzle mouthpiece of the plasma generator and/or to use a water steam as the plasma-generated gas which has a radiant emittance higher than an air.

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REFERENCES


GINZBURG, I.P., (1975), "Friction and heat transfer at the motion of gas mixture", (in Russian), Publication of the Leningrad University, Leningrad.


