Second International Conference on CFD in the Minerals and Process Industries
CSIRO, Melbourne, Australia
6-8 December 1999

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

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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

ρ	density
p	pressure
μ	dynamic viscosity
$\vec{U}$	vector of averaged gas velocity
$\vec{u}$	vector of particles velocity
H	enthalpy of gas
C_i	mass fraction of ***i***-th species
M_i	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-temperatute 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 allow 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 Gusinoozersk 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).

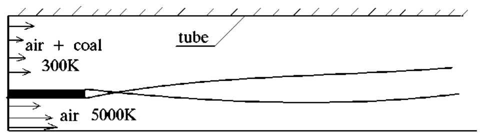


Figure 1: Scheme of pulverized-coal aeromixture lighting by the low-temperature plasma jet in a burner.

The air heated in an electric arc plasma generator to 5000K is supplied through the central part of the tube via the mouthpiece. The polydispersive 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 at 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 ρ_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; ρ_0 is the density of the starting fuel. The volatile matter is assumed to contain hydrocarbons, water, and carbon dioxide: $V = \{C_nH_m, H_2O, CO_2\}$. 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):

$$O_2 \leftrightarrow O+O, \quad N_2 \leftrightarrow N+N, \quad NO \leftrightarrow N+O$$

$$O_2+N \leftrightarrow NO+O, \quad N_2+O \leftrightarrow NO+N$$

$$N_2+O_2 \leftrightarrow NO+NO$$

Their rates are determined by the Arrhenius law. We also take into account the generalized combustion reaction of hydrocarbons:

$$C_nH_m + (n + \frac{m}{4})[\alpha O_2 + 2(1-\alpha)O] \to nCO_2 + \frac{m}{4}H_2O$$

where α 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_nH_m is determined by formula

$$J_{C_nH_m} = \min\{A\rho C_{C_nH_m}\,\varepsilon/k,\, A\rho C_{O_2}\,\varepsilon/k,\, A\rho(C_{H_2O} + C_{CO_2})/(1+s)\,\varepsilon/k\}$$

where $s = (n + m/4)\,M_{O_2}/M_{C_nH_m}$ 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:

$$C + [\alpha O_2 + 2(1-\alpha)O] \to CO_2$$

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 tempereature 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 Kuvaev, 1986), which also takes into account the diffusive kinetic character of this process.

Mathematical model

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

$$\frac{du_i}{dt} = C_{Ri}(u - u_i) - \frac{3}{4}\frac{\rho}{\rho_{bi}}(v - v_i)[\omega_i - \frac{1}{2}(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y})] \equiv F_1 \qquad (1)$$

$$\frac{dv_i}{dt} = C_{Ri}(v - v_i) + \frac{3}{4}\frac{\rho}{\rho_{bi}}(u - u_i)[\omega_i - \frac{1}{2}(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y})] + \frac{9.69}{\pi\rho_{bi}d_i}\operatorname{sign}(\frac{\partial U}{\partial y})(u - u_i) \times \sqrt{\rho\mu\left|\frac{\partial U}{\partial y}\right|} \equiv F_2 \qquad (2)$$

$$\frac{d\omega_i}{dt} = C_{\omega i}[\frac{1}{2}(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}) - \omega_i] \qquad (3)$$

$$\frac{dm_{ci}}{dt} = -\beta\frac{A_c\exp(-E_c/RT_i)\rho C_{O_2}}{1 + A_c\exp(-E_c/RT_i)d_i/(D\cdot Nu_{O_2})} \equiv J_c \qquad (4)$$

$$\frac{dm_{vi}}{dt} = -\frac{A_v\exp(-E_v/RT_i)m_{vi}}{1 + 1/6\,A_v\exp(-E_v/RT_i)D_v} \equiv J_v \qquad (5)$$

$$c_i m_i\frac{dT_i}{dt} = \pi d_i^2[\alpha_i(T - T_i) + \varepsilon_p\sigma(T_{avg}^4 - T_i^4)] + q_cJ_c - q_vJ_v \equiv Q \qquad (6)$$

$$C_{Ri} = \frac{18\mu}{\rho_{bi}d_i^2}[1 + 0.179\,Re_{pi}^{1/2} + 0.013\,Re_{pi}],$$

$$C_{\omega i} = \frac{60\mu}{\rho_{bi}d_i^2},\quad Re_{pi} = \frac{d_i\rho\left|(\vec{U} + \vec{u})' - \vec{u}_i\right|}{\mu}$$

where m_i, m_{ci}, m_{vi} are the mass of particle and the masses of carbon and volatile matter in it; ρ_{bi}, d_i are the density of a particle and its diameter; q_c, q_v are the heat release of the combustion reaction of the coke residue and volatile matter accordingly; β is the efficient stoichiometric coefficient; C_{Ri}, α_i are the drag coefficient and the heat transfer coefficient; ε_p, σ are the emissivity factor of the particle and the Stefan-Boltzmann constant; T_{avg} is the section-averaged radiation temperature. The vector $\vec{u}'$ 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, *i, k* = 1,2):

$$\frac{\partial}{\partial x_k} y\rho U_k = yJ \tag{7}$$

$$\frac{\partial}{\partial x_k} y\rho U_i U_k + \frac{\partial}{\partial x_k} yp = \frac{\partial}{\partial x_k} y[\mu\tau_{ik} - \rho < u_i' u_k' >] + \\ + y\{n_p << F_i >> + U_i J - J << (U_i - u_i) >>\} \tag{8}$$

$$\frac{\partial}{\partial x_k} y\rho H U_k = \frac{\partial}{\partial x_k} y[\lambda \frac{\partial T}{\partial x_k} - \rho < h' u_k' > + (\mu\tau_{ik} - \\ - \rho < u_i' u_k' >)\frac{\partial U_i}{\partial x_k}] + y n_p (<< Q >> + << (\vec{U}, \vec{F}) >>) \tag{9}$$

$$\frac{\partial}{\partial x_k} y\rho C_i U_k = \frac{\partial}{\partial x_k} y[(\rho D_i + \frac{\mu_t}{Sc_t})\frac{\partial C_i}{\partial x_k}] + yJ_i \tag{10}$$

$$\frac{\partial}{\partial x_k} y\rho k U_k = \frac{\partial}{\partial x_k} y[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_k}] - y\{\rho < u_i' u_k' > \times \\ \times \frac{\partial U_i}{\partial x_k} + \rho\varepsilon + k n_p << \Phi_S >> - kJ\} \tag{11}$$

$$\frac{\partial}{\partial x_k} y\rho \varepsilon U_k = \frac{\partial}{\partial x_k} y[(\mu + \frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_k}] - y\{C_{\varepsilon 1}\frac{\varepsilon}{k}\rho < u_i' u_k' > \times \\ \times \frac{\partial U_i}{\partial x_k} + C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k} + C_{\varepsilon 3}\varepsilon n_p << \Phi_S >> - \varepsilon J\} \tag{12}$$

$$p = \rho R_0 T \sum_{i=1}^{8} C_i / M_i \tag{13}$$

$$\rho < u_i' u_k' > = \frac{2}{3}\rho k \delta_{ik} - \mu_t \tau_{ik}, \quad \mu_t = C_\mu \rho \frac{k^2}{\varepsilon}$$

$$\rho < h' u_k' > = -\frac{\mu_t}{Pr_t}\frac{\partial H}{\partial x_k}, \quad \tau_{ik} = (\frac{\partial U_i}{\partial x_k} + \frac{\partial U_k}{\partial x_i} - \frac{2}{3}\frac{\partial U_l}{\partial x_l}\delta_{ik})$$

$$J = n_p (<< q_c >> + << q_v >>)$$

where $i = \{O, O_2, N, N_2, NO, C_nH_m, CO_2, H_2O\}$.

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 $V_{m,n}$:

$$n_p = \frac{\sum_k \eta_k \tau_k}{V_{m,n}}, \quad k \in (m,n), \quad << \varphi >> = \frac{\sum_k \eta_k \int_0^{\tau_k} \varphi_k dt}{\sum_k \eta_k \tau_k}$$

$$<< \Phi_s >> = << 2\sum_{j=1}^{2} F_j \left(1 - \frac{\tau_L}{\tau_L + 1/C_R}\right) >>, \quad \tau_L = 0.35 k/\varepsilon$$

where n_p is the particle concentration in a cell, η_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, φ is any of $q_c, q_v, F_i, Q,$ 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 implict 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

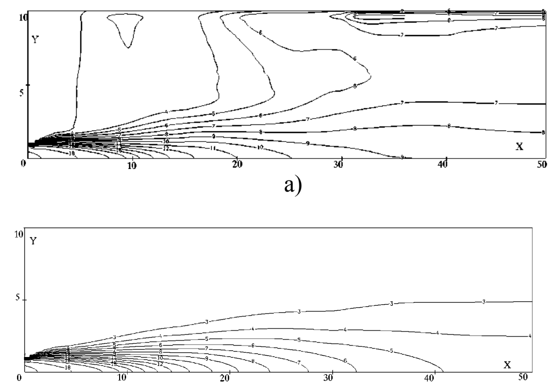
We calculated the lighting process for the case of a polydispersive pulverized-coal flow (particles of three sizes were used) at the value of the basic parameters: $T_0 = 5000$ K, $T_b = 300$K, $R_0 = 0.015$ m,

$d_1 = 8 \cdot 10^{-5}$ m, $d_2 = 10^{-4}$ m,

$d_3 = 1.2 \cdot 10^{-4}$ m, $w_{p1} = 0.3$, $w_{p2} = 0.5$, $w_{p3} = 0.2$,

$U_0 = 300$ m/s, $U_b = 10$ m/s, $R_b = 0.15$m.

Here T_0, T_b are the temperatures of the jet and the wake flow at the inlet section; R_0, R_b are the radiuses of the nozzle and the muffle, respectively; d_i, w_{pi} are the diamters of the particles 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 those in (Volkov et al., 1980).



a)

b)

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 refered 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 $\Delta T = 250$ 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).

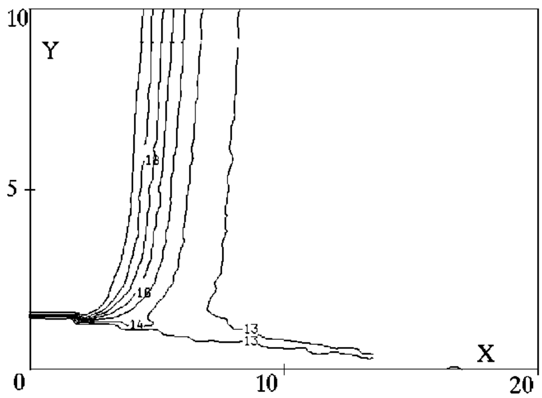


Figure 3: Isolines of the volatile matter content in the coal particles

This may be due to the dominant role of the radiative heat transfer in the ignition process since the residence time of particles in the peripheral region of the flow turns out to be the longest. This conclusion is confirmed by the dynamics of the release of the volatile matter, which is shown in Figure 3 as the position of the isolines of averaged fraction of total mass $<< m_v >>$ in the coal particles.

This also implies that for the given ignition scheme the radiative heat transfer is of major importance in release process of the volatile matter from the coal particles. It is evident from isotherm positions in Figure 2a that its ignition occurs well downstream.

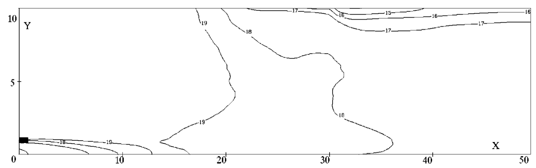


Figure 4: Isolines of molecular oxygen.

Figure 4 gives the pattern of the distribution of the isolines of the molecular oxygen concentration. This pattern also supports the conclusion that the coke particles start burning in the peripheral part of the flow after the volatile matter ignite. Of considerable interest is the study of the distribution of the fraction of atomic oxygen in the flow field because even the presence of its moderate concentrations can significantly step up ignition process. Figure 5 shows the position of the corresponding isolines.

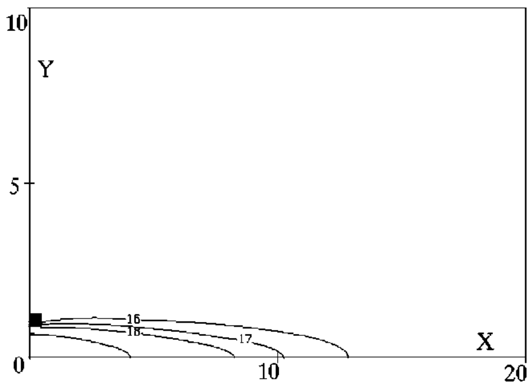


Figure 5: Isolines of atomic oxygen.

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 emmitance 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 emmitance higher than an air.

ACKNOWLEDGEMENTS

The authors thank the Russian Foundation of Fundamental Research for support of this study (grant 97-01-00858) and Ministry of General and Professional Education of Russia (grant 11 Гр -98 in the field of power engineering)

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