Journal of Applied Mechanics and Technical Physics, Vol. 39, No. 3, 1998

MATHEMATICAL SIMULATION OF IGNITION OF A COAL–DUST SUSPENSION IN AIR BY A LOW-TEMPERATURE PLASMA JET

A. D. Rychkov and M. F. Zhukov[1]

UDC 532.529+621.793

The process of aerosuspension ignition of a suspension in air in a pulverized-coal burner with a preswitched muffle by a central axisymmetric air stream heated in an electric-arc plasmatron to a temperature of about ≈5000 K is numerically simulated. This process is the basis of a new fuel-oil-free method of ignition of the boilers of thermal power stations. The method is rather promising from the viewpoint of both economy and ecology. The goal of numerical simulation is to study the process of ignition of coal particles in the flow and to identify the conditions necessary for the transition to self-sustained burning of a coal–dust mixture. The results obtained revealed the significant role of radiative heat transfer in initializing the burning process of solid fuel particles.

One interesting example of application of plasma technology in boiler engineering is the use of a low-temperature plasma jet for ignition of boilers of thermal power stations (TPS) and stabilization of a coal–dust plume [1]. This allows one to avoid using traditional fuels, such as fuel oil or natural gas, to automate the ignition process, to increase the burning efficiency of the solid fuel, and to reduce the emission of noxious gases into the atmosphere, i.e., to improve significantly the economic and ecological performance of TPS. Full-scale experiments on plasma ignition of coal-dust boilers have already been performed on the Gusinoozersk hydropower station and several thermal power stations in Mongolia, and this new technology has been applied in the industry. Nevertheless, many questions associated with better comprehension of the specifics of physicochemical processes that occur during the interaction of a plasma jet and a particle-laden flow are still open and require additional theoretical and experimental study.

In the present work, we simulate numerically the process of ignition of a suspension in air in a pulverized-coal burner by a central axisymmetric jet of low-temperature plasma. The ignition of coal particles in the flow has been studied, and the conditions necessary for a transition to self-sustained burning of a coal-dust mixture have been found.

Figure 1 shows a flow pattern in a pulverized-coal burner which is a pipe (muffle). The air, heated in an electric-arc plasmatron to a temperature of 5000 K, is injected through a nozzle into the central part of this burner. A polydispersed particle-laden flow with the weight fraction of the solid fuel, which is typical of pulverized-coal TPS burners, is injected into the periphery of the burner. The flow in the jet and in the peripheral low-velocity concurrent two-phase stream was assumed to be axisymmetric and turbulent, and the force and thermal interaction between the carrier gas and the particles and all the basic stages of the process of coal-dust particle ignition, including the output of volatiles and their burning and ignition and the burning of the coke residue, were taken into account.

A model of a coal particle with a rigid ash frame [2] was used to describe these processes. In this model, the particle size remains unchanged during burning, and only the particle composition (and, hence,

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Institute of Computing Technology, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090. [1]Institute of Theoretical and Applied Mechanics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 39, No. 3, pp. 134–140, May–June, 1998. Original article submitted October 2, 1996.

0021-8944/98/3903-0441 $20.00

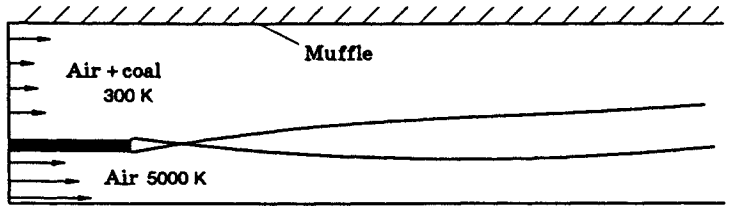

Fig. 1

its density) changes. The particle density ρ_i was defined as

$$\rho_i = \rho_0(C + V + A),$$

where C, V, and A are the mass fractions of carbon, volatiles, and ash, respectively, and ρ_0 is the density of the initial fuel. It was assumed that the volatiles include hydrocarbons, water, and carbon dioxide: $V = \{C_nH_m,\ H_2O,\ CO_2\}$. In the gas phase, we took account of the nonequilibrium chemical dissociation and exchange reactions proceeding in a low-temperature plasma [3]; the reaction rates were determined from the Arrhenius law

$$\begin{array}{ll} O_2 \rightleftarrows O + O, & N_2 \rightleftarrows N + N, \\ NO \rightleftarrows NO + O, & O_2 + N \rightleftarrows NO + O, \\ N_2 + O \rightleftarrows NO + N, & N_2 + O_2 \rightleftarrows NO + NO, \end{array}$$

and the overall burning reaction of hydrocarbons

$$C_nH_m + \left(n + \frac{m}{4}\right)(\alpha O_2 + 2(1-\alpha)O) \longrightarrow nCO_2 + \frac{m}{4}H_2O,$$

where α is the relative fraction of molecular oxygen in the "generalized" oxidizer which consists of a mixture of molecular and atomic oxygen. It was assumed that the limiting stage of the burning process is the turbulent mixing described by the model of splitting of turbulent vortices [4]. In this case, for example, the mass rate of C_nH_m burning is found to be

$$J_{C_nH_m} = \min\{A\rho C_{C_nH_m}\varepsilon/k, A\rho C_{O_2}\varepsilon/k, A_1\rho(C_{H_2O} + C_{CO_2})/(1+s)\varepsilon/k\},$$

where $s = (n + m/4)M_{O_2}/M_{C_nH_m}$ is the stoichiometric coefficient, and A and A_1 are empirical constants.

It was assumed that carbon burning with excess oxidizer follows the one-stage reaction scheme

$$C + (\alpha O_2 + 2(1-\alpha)O) \longrightarrow CO_2.$$

A characteristic feature of this flow is that, near the nozzle exit cross section, there is a region free of particles into which they gradually penetrate owing to the mechanism of turbulent diffusion. At a certain distance from this cross section, the particles can even cross the centerline, which involves some difficulty in describing their motion within the framework of a continuum approach. Therefore, we considered the motion of particles within the framework of a trajectory method of test particles proposed by Crowe [5], and the effect of turbulent oscillations of the carrying gas on the particle motion was taken into account on the basis of a random walk technique [6]. The test particle is understood as a "packet" of particles of the same size which move along a common trajectory. Since the particles enter the region of mixing of a plasma jet and a concurrent flow, where the flow is close to stratified, along with aerodynamic drag forces, the Saffman force and particle rotation, which were assumed to be spherical, were taken into account. Both convective and radiative heat exchanges between the gas and the particles were considered; we note that at this stage of investigation, the latter was determined by the simplest method: via the mean radiation temperature of the medium which takes into account the thermal radiation from the plasma jet.

The yield of volatiles was calculated on the basis of the one-component scheme of a first-order reaction whose rate was found using a diffusion-kinetic dependence which takes into account both the kinetics of the

process described by the Arrhenius law and the diffusion drag induced by the volatiles passing through the mass of fuel particles [2]. In calculating carbon (coke residue) burning, we used a semiempirical dependence [7] which incorporates the diffusion-kinetic character of this process.

Written along the trajectory of the ith particle, the system of equations of particle motion is of the form

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

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

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

$$\frac{dm_{ci}}{dt} = -\beta\frac{A_c\exp(-E_c/RT_i)\rho C_{O_2}}{1 + A_c\exp(-E_c/RT_i)d_i/(D\mathrm{Nu}_{O_2})} \equiv J_c; \tag{4}$$

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

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

$$C_{Ri} = \frac{18\mu}{\rho_{bi}d_i^2}[1 + 0.179\mathrm{Re}_{pi}^{0.5} + 0.013\mathrm{Re}_{pi}], \qquad C_{\omega i} = \frac{60\mu}{\rho_{bi}d_i^2}, \qquad \mathrm{Re}_{pi} = \frac{\rho|\mathbf{U}-\mathbf{U}_i|}{\mu},$$
$$u = U + u', \qquad v = V + v',$$

where u_i, v_i, and ω_i are the components of the velocity vector $\mathbf{U}_i$, T_i is the particle temperature, U, V, u', and v' are the average and fluctuating parameters of the flow of the carrying gas (the velocity-vector components), T is the mean temperature of the gas, T_{av} is the radiation temperature averaged over the cross section, m_i, m_{ci}, and m_{vi} are the masses of the particle, carbon, and the volatiles contained in the particle, ρ_{bi} and d_i are the particle-material density and the particle diameter, q_c and q_v are the thermal effects of the coke-residue burning and volatile-emission reactions, and β is an effective stoichiometric coefficient.

The values of u' and v' were found as random quantities with the Gaussian distribution and the root-mean-square deviation equal to $(2/3)k$ [6].

To describe the motion of the carrying gas, we used the Reynolds-averaged system of Navier–Stokes equations closed by a standard k–ε model of turbulence that takes into account the interphase interactions both in the average and fluctuating flows. For the case of an axisymmetric flow, the system of these equations was written in the following form (summation was performed over repeat subscripts; i, $k = 1, 2$):

$$\frac{\partial}{\partial x_k}y\rho U_k = yn_p(\langle\langle q_c\rangle\rangle + \langle\langle q_v\rangle\rangle); \tag{7}$$

$$\frac{\partial}{\partial x_k}y\rho U_iU_k + \frac{\partial}{\partial x_k}yP = \frac{\partial}{\partial x_k}y[\mu\tau_{ik} - \rho\langle u_i'u_k'\rangle] + yn_p\langle\langle F_i\rangle\rangle; \tag{8}$$

$$\frac{\partial}{\partial x_k}y\rho HU_k = U_k\frac{\partial}{\partial x_k}yP + \frac{\partial}{\partial x_k}y\left[\lambda\frac{\partial T}{\partial x_k} - \rho\langle h'u_k'\rangle + (\mu\tau_{ik} - \rho\langle u_i'u_k'\rangle)\frac{\partial U_i}{\partial x_k}\right] + yn_p(\langle\langle Q\rangle\rangle + \langle\langle(\mathbf{U},\mathbf{F})\rangle\rangle); \tag{9}$$

$$\frac{\partial}{\partial x_k}y\rho U_kC_j = \frac{\partial}{\partial x_k}y\left[\left(\rho D_j + \frac{\mu_t}{\mathrm{Sc}_t}\right)\frac{\partial C_j}{\partial x_k}\right] + yJ_j; \tag{10}$$

$$\frac{\partial}{\partial x_k}y\rho U_kk = \frac{\partial}{\partial x_k}y\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_k}\right] - y\left(\rho\langle u_i'u_k'\rangle\frac{\partial U_i}{\partial x_k} - \rho\varepsilon - kn_p\langle\langle\varepsilon_s\rangle\rangle\right); \tag{11}$$

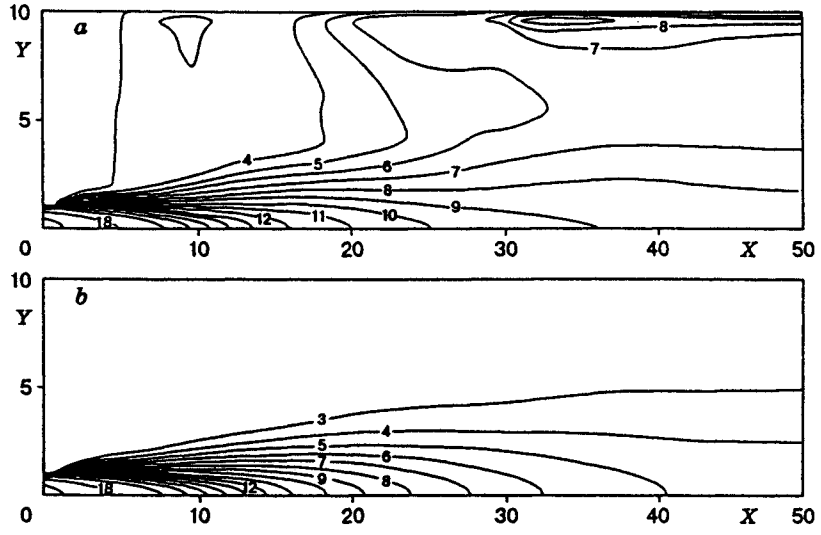

Fig. 2

$$\frac{\partial}{\partial x_k} y\rho U_k \varepsilon = \frac{\partial}{\partial x_k} y\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_k}\right] - y\left(C_{\varepsilon 1}\frac{\varepsilon}{k}\rho\langle u_i' u_k'\rangle \frac{\partial U_i}{\partial x_k} - C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k} - C_{\varepsilon 3}\varepsilon n_p\langle\langle \varepsilon_s\rangle\rangle\right); \tag{12}$$

$$P = \rho R_0 T \sum_j \left(\frac{C_j}{M_j}\right), \quad \tau_{ik} = \left(\frac{\partial U_i}{\partial x_k} + \frac{\partial U_k}{\partial x_i} - \frac{2}{3}\frac{\partial U_l}{\partial x_l}\delta_{ik}\right), \quad \rho\langle u_i' u_k'\rangle = \frac{2}{3}\rho k\delta_{ik} - \mu_t \tau_{ik},$$

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}, \qquad \rho\langle h' u_k'\rangle = -\frac{\mu_t}{\mathrm{Pr}_t}\frac{\partial H}{\partial x_k}, \tag{13}$$

where ρ, $\mathbf{U} = \{U_1, U_2\} \equiv \{U, V\}$, H, P, T, C_j, and M_j are the averaged parameters of the flow [density, velocity vector, enthalpy, pressure, temperature, and concentrations of the chemically reacting components of a mixture and their molecular weights ($j = \{\mathrm{O}, \mathrm{O}_2, \mathrm{N}, \mathrm{N}_2, \mathrm{NO}, \mathrm{C_nH_m}, \mathrm{CO}_2, \mathrm{H}_2\mathrm{O}\}$)], u_1', u_2', and h' are the corresponding fluctuating parameters, $\mathbf{F}$ is the vector of force interaction between the gas and the particles, and Sc_t is the turbulent Schmidt number.

The terms in double angular brackets allow for interphase interactions. They are determined by means of the spatial-temporal averaging of the bracketed quantities over the sections of the test particle trajectories crossing the boundaries of a computational cell of the difference grid $V_{m,l}$:

$$n_p = \sum_k \eta_k \tau_k / V_{m,l}, \quad k \in (m,l), \qquad \langle\langle\varphi\rangle\rangle = \sum_k \eta_k \int_0^{\tau_k} \varphi\, dt \Big/ \sum_k \eta_k \tau_k,$$

$$\langle\langle \varepsilon_s\rangle\rangle = \left\langle\left\langle 2\sum_{i=1}^{2} F_i\left(1 - \frac{\tau_L}{\tau_L + 1/C_{Ri}}\right)\right\rangle\right\rangle, \qquad \tau_L = 0.35k/\varepsilon.$$

Here n_p is the particle concentration in a cell, η_k is the number of particles in the "packet" of test particles along the kth trajectory, which is determined from the conditions imposed in the initial cross section, and φ is the law of averaging of the quantities q_c, q_v, F_i, Q, $\mathbf{U}$, and $\mathbf{F}$ in Eqs. (8) and (9).

Only the initial conditions in the inlet cross section of the burner were set for system (1)–(6). During their motion, the particles can be reflected from the tube wall and cross the centerline. The boundary conditions for system (7)–(13) were typical of internal turbulent flows: the no-slip condition on the tube wall, the symmetry conditions on the centerline, and the "mild" boundary conditions in the exit cross section. It was assumed that there is a developed turbulent flow in the inlet cross section, with the profile of the longitudinal velocity-vector component changing near the solid walls in accordance with the "law of 1/7."

To solve system (1)–(6) which is classified as a "stiff" system, we used an implicit A-stable difference

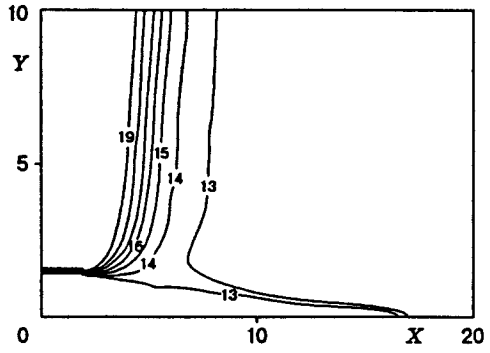

Fig. 3

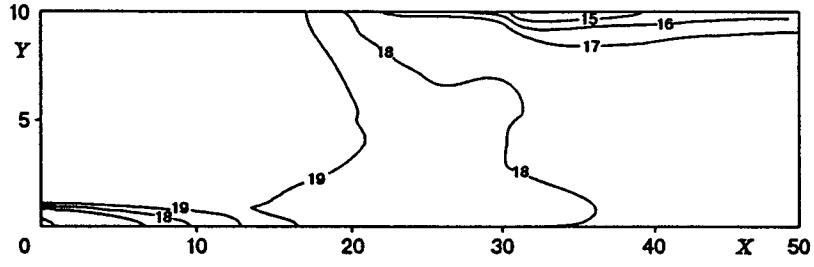

Fig. 4

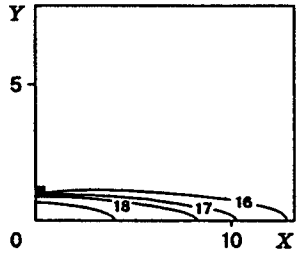

Fig. 5

scheme of second order [8]. System (7)–(13) was solved by the pseudo-transient method using a semi-implicit difference scheme proposed by Patankar [9]. The interphase interactions were taken into account by iterations in the sequential solution of the systems of equations [8].

The ignition process was calculated for the case of a polydispersed particle-laden flow (the particles of three fractions were used) for the following values of the governing flow parameters: $T_0 = 5000$ K, $T_b = 300$ K, $R_0 = 0.015$ m, $R_b = 0.15$ 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/sec, and $U_b = 10$ m/sec, where T_0 and T_b are the temperatures of the jet and the concurrent flow in the inlet cross section, R_0 and R_b are the radii of the nozzle and the muffle, d_i and w_{pi} are the particle diameters and the relative weight fraction of each component, and U_0 and U_b are the gas velocities in the jet and the concurrent flow. The force and thermal interactions between the different fractions of particles were ignored. The mass composition of the fuel and the empirical coefficients in Eqs. (1)–(13) were assumed to be the same as in [2].

Figure 2 shows isotherms for two-phase (a) and pure gas (b) flows (the curves are plotted with step $\Delta T = 250$ K, and all the linear dimensions are normalized to the radius of the nozzle exit cross section). It is seen that the jet temperature decreases faster near the nozzle exit cross section due to heat exchange with the particles; however, as the volatiles and the coke residue are formed and burn, the temperature in the flow field becomes higher than in the case of a pure gas. It is of interest that the ignition of coal particles in the flow outside the plasma jet occurs near the tube (muffle) wall. This can be related to the leading role of radiative heat transfer during ignition, since the largest residence times are observed in the peripheral region of the flow. This conclusion is supported by the dynamics of the volatile yield, which is shown in Fig. 3 as isolines of their averaged mass fractions $\langle\langle m_v \rangle\rangle$ in the coal particles. This dynamics also testifies that radiative heat transfer plays the main role in the process of volatile release from coal particles for this technological scheme of ignition. Judging from the positions of the isotherms in Fig. 2a, particle ignition occurs much farther downstream. This idea is also supported by the distribution of the isolines of the molecular oxygen concentration (Fig. 4), which confirms that the burning of the coke residue begins in the flow periphery after the volatiles ignite.

Of great interest is to study the distribution of atomic oxygen in the flow field (Fig. 5), since the presence of even comparatively small concentrations of molecular oxygen can substantially intensify the ignition process. Based on Fig. 5, we can conclude that in the technological scheme of ignition considered, almost all atomic oxygen is consumed in recombination reactions near the nozzle exit in the particle-free region, and its effect on the ignition of fuel particles is insignificant. Apparently, its role will be more significant if some part of a particle-laden flow is injected through the nozzle, i.e., passes through a low-temperature plasma flow.

This work was supported by the Russian Foundation for Fundamental Research (Grant No. 97-00-0858).

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