Numerical Simulation Model of Swirl Burner Pulverized Coal Flame

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Abstract: A mathematical model for the computer simulation of pulverized coal combustion in axisymme-tric furnace with swirl burner is presented. The model is based on 2 equation k-ε turbulence model, considering the presence of the solid phase via the additional source terms in the gas phase equations (PSI-Cell method). The disperse phase is simulated through history of location, velocity, mass and temperature of particular particles by using the Lagrangian Stochaistic Deterministic (LSD) model. Coal devolatilization, homogeneous and heterogeneous chemical reaction processes are simulated together via the global combustion model using own reaction kinetics data. Analysis of influence that the most significant parameters (swirl number, particle size), and coal characteristics, exert upon the combustion process has been performed.

Key words: combustion, pulverized coal, swirl burners, computer simulation, turbulence flow

1 Introduction

Use of swirl burners for pulverized coal combustion is wide due to positive influence of swirl upon flame stabilization and intensification. Flow field is such that in central zone of swirl from burner, hot gases recirculate, ensuring stable burning of coal particles.

Complex mathematical model for computer simulation of pulverized coal flame in an axisymmetric furnace is developed; based on k-ε single phase model, treating solid phase via extra source terms in gas equations. Simulations allowed the analysis of influence that swirl number, particle size, excess air, and coal type, exert on the combustion process.

2 Mathematical model

Swirl burners introduce coal particles with primary air. Secondary swirled air, via an annular opening, induces recirculation of hot gases, for enough swirl, ensuring stable ignition and combustion of coal particles. Gas phase is axisymmetric, turbulent and incompressible. Stationarity is assumed for time mean values of velocity, temperature, etc. Flow is described by elliptic partial differential equations. Two-equation k-ε model of turbulence is used [1].

Conservation equations can be expressed as a single equation for generalized variable ϕ, in cylindrical coordinates:

$$\frac{\partial}{\partial x}(\rho U\phi)+\frac{1}{r}\frac{\partial}{\partial r}(r\rho V\phi)=\frac{\partial}{\partial x}\left(\Gamma_\phi\frac{\partial\phi}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma_\phi\frac{\partial\phi}{\partial r}\right)+S_\phi \quad (1)$$

In order to define completely the turbulent gas flow field, it was needed to solve 9 equations of type (1):

- continuity equation,
- 3 momentum equations (axial, radial and tangential),
- 2 equations of the k-ε model of turbulence,
- energy conservation equation,
- 2 continuity equations for flue gas (O_2 , CO_2+H_2O).

The flow field is computed (axial, radial and tangential components of the mean velocity, temperature, fields of k and ε, concentration of flue gas components etc.), that is initial data for iteration solving gas flow, motion of particles, and interphase heat and mass transfer. PSI-Cell concept, treats particles through added source terms in gas equations. Disperse phase is treated via history of

particles by LSD model [3]. One obtains local values of velocity, temperature and concentration of particles and - particle trajectories. Energy equation for particles is solved where change of particle enthalpy equals to heat transfer between phases: forced convection from gas to sphere, and radiation - solved by the commonly used 6-flux method.

Devolatilizing, homogene and heterogene combustion are treated together, using global reaction rate based on own experimental data [4]. Since combustion model is complex itself, one tends to simplify each of its components but to preserve the accuracy. Also, although results exist on devolatilization of Serbian lignites, [5], there is a significant lack of data for rate of combustion of volatiles and char for these coals.

For simplicity, gas is assumed to consist of inert N_2 , unused O_2 and - products of full combustion, i.e. CO_2 and H_2O and - that C and H from fuel react with same (global) rate by single step reactions with O_2 from fuel and gas. Coal reacts at outer surface and inside pores (unreacted core regime) by reducing its volume, and the reaction is controlled by both kinetics and diffusion:

$$\frac{dm_p}{d\tau} = \rho_p \frac{\pi}{2} \cdot d_p^2 \frac{d(d_p)}{d\tau} = -r_p \qquad (2)$$

Chemical reaction rate for kinetically - diffusionally controlled reaction is defined by the expression:

$$r_p = \frac{A_p \upsilon M_p C_{mol}^{ox}}{1/k_r + 1/k_d} \qquad (3)$$

The set of differential equations (1) is solved by control volume method of Patankar & Spalding [6].

Algorithm SIMPLE for solving elliptic equations in TEACH-T code was modified including computation of particle motion, mass and temperature and particle source terms of interphase heat and mass exchange.

3 Parametric analysis

In modelled case burner introduces primary air with monodisperse particles through 21.6/27.2 mm annulus at 20.6 m/s and 300 K. Secondary air enters through a 30.2/43.9 mm annulus at 25.4 m/s and 313 K with swirl (S). Mass flowrate, temperature and density of particles at furnace inlet are 20.8 g/s, 300 K and 1500 kg/m^3, respectively. A 45° and 43.9/107 mm diffuser conveys the flow into 6.2 m furnace of 0.8 m inner diameter. Kolubara coal (pit Polje D - denoted as PD), is chosen, of ultimate analysis (in mass %): C(40.5), H(3.9), O(17.2), N(0.8), S(1.1), A(25.9), W(10.4). The heating value of this coal is H_d=16.188MJ/kg.

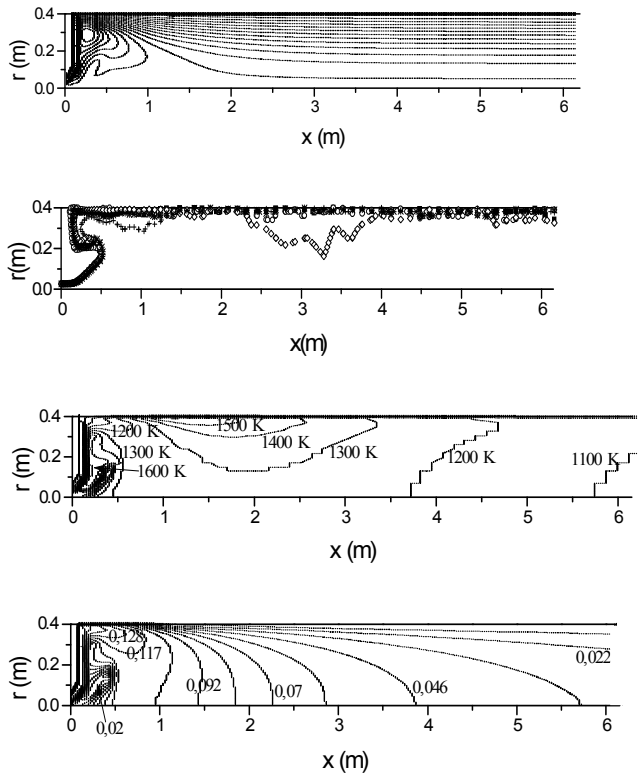

Fig. 1: Results of computation for regime (d_P=150 μm, tgφ_S=1.0, λ=1.05).

Pre-exponential term and activation energy in the Arrhenius expression for reaction rate are: k_0=8900 m/s and E=95400 kJ/kmol, (Saljnikov et al., 1995). Furnace wall is assumed at 800 K, and particles are assumed to be divided at 300 different trajectories.

Parametric analysis was done varying diameter of particles (75, 150, 350 μm), angle between velocity of secondary air and the axis - tgφ_S (0.6, 0.8 and 1.0). Simulation was done for 3 coals, testing their flames with same flow and temperature boundary conditions.

Figure 1 is the "reference" case (d_P=150 μm, tgφ_S=1.0, λ=1.05) - coal PD. Flow field - Figure 1a. Swirl forms the central recirculation zone. 5, of 300 computed trajectories, are shown in Figure 1b. Due to inertia, particles penetrate the central recirculation and move along its streamlines. Moving upstream, particles are caught by main stream that takes them to wall, along which they flow downstream. Also, particles spread due to weaker swirl. Temperature field, Fig. 1c, complies to flow field and trajectories. In furnace, particles meet recirculated hot gases and

burn. Peak temperatures are in zone of reverse flow of particles, travel to wall and initial flow along wall. Of 5 particles in Figure 1b, each representing 1/5 of total mass, only one fully burns before the exit (at x=5 m). Caught by turbulence, it travels through zone richer in oxygen. Combustible part of particles burnt out at furnace exit is between 80 and 100 percent, while at about x=1 m it is 70 to 80 %.

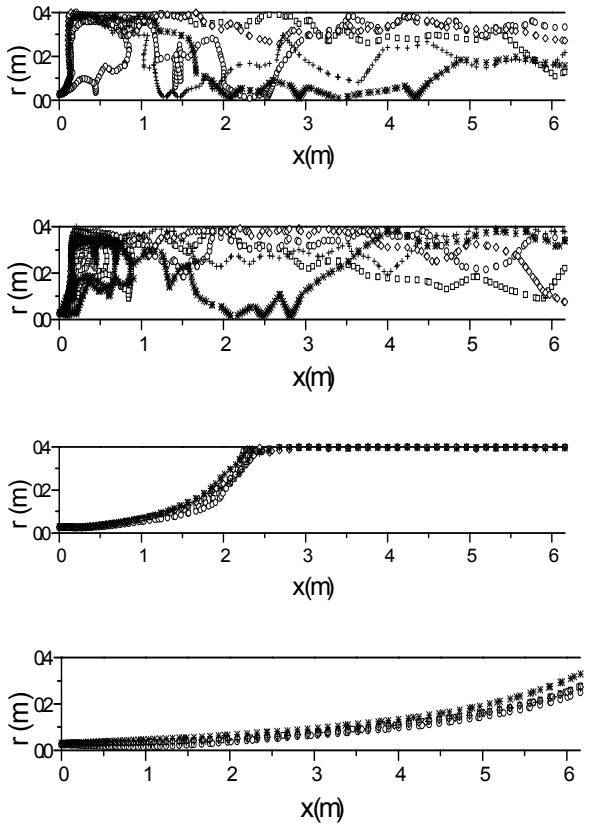

Figure 2: Results of computation for the polydisperse coal ($tg\varphi_S$=1.0, λ=1.05).

3.1 Influence of particle size

The effect of size of monodisperse particles is treated by comparing results for same swirl ($tg\varphi_S$=1.0), excess air (λ=1.05) & different diameter of particles. Computations were done for polydisperse coal from the same pit, divided into 5 fractions (25, 70, 145, 350 and 750 μm). Same effects were observed as for flames of the fractions, Figure 2. 350 μm particles, 12.7 times more massive than 145 μm ones, are not caught by central recirculation and are subject to swirl effect later. Majority turns to periphery at x=1.5 m, the remainder spreads later (at x=2.5 to 3 m).

Burnout degree at exit is larger for particles passed through oxygen rich zone turning to the wall earlier. We see strong slowdown of combustion while they travel down the wall, through zone poor in oxygen. Coal the combustible part of which has burnt about 90% out before x=2.9 m - finishes its combustion at x=3.2 m, next particle at 4.1 and 4.7 m respectively, while the third particle at 5.0 m and only 2% more to the furnace exit (x=6.2 m). Large part of them continues burning before they leave the furnace. 70 μm particles are 8 times less massive than the 145 μm ones. Effect of penetration into central recirculation zone is weak. Due to lower mass, they follow the streamlines of main stream at the inlet. Entering the furnace, coal particles are caught by main current and taken to the wall. Some are caught by the central recirculation zone and recirculate once or several times within it. When swirl effect weakens, less massive particles are caught by turbulence which is observed from the shape of trajectories, leave wall at x=0.5 to 1 m and spread throughout the furnace. All 5 particles finish combustion within the furnace, 4 at about x=3.5 m, those caught by central recirculation burn out fully in the third recirculation

4 Conclusion

A complex mathematical model for the computer simulation of pulverized coal flame in axisymmetric furnace with swirl burner is presented. It is based upon k-ε turbulent flow model, considering the solid phase via source terms in the gas phase equations (PSI-Cell). Particles are simulated via history of location, mass, temperature and velocity (LSD model). Heat radiation is simulated via the 6-flux method. Devolatilization, homogeneous - and heterogeneous combustion are simulated by global combustion scheme using own chemical reaction kinetics data.

Influence of significant parameters (swirl number, particle size), and coal type, upon combustion, was analysed. Results prove that simulation model gives physically / chemically logical and expected response to change of all parameters, which is its qualitative verification. It is sensitive to effect of varying the coal type when simulating combustion of coal from different origin in same flow and temperature conditions. The model can be applied for simulating pulverized coal combustion for cases different in geometry, flow and temperature conditions, origin of coal etc. These

conclusions are proved by comparison with experimental results.

Nomenclature:

A_p particle area
d_p particle diameter
k turbulence kinetic energy
k_d diffusion coefficient
k_r reaction rate constant
m_p particle mass
r_p reaction rate
U,V gas velocity axial, radial component
x,r axial, radial coordinate
Γ_ϕ diffusion coefficient
ε dissipation of kinetic energy of turbulence
υ stoichiometric coefficient
λ excess air ratio
ϕ generalized variable
φ angle of velocity vector to x-axis

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