

MODELING OF PULVERIZED COAL COMBUSTION STABILIZATION BY MEANS OF PLASMA TORCHES

by

**Miroslav SIJERČIĆ, Srdjan BELOŠEVIĆ,
and Predrag STEFANOVIĆ**

Original scientific paper

UDC: 662.62:66.088

BIBLID: 0354-9836, 9 (2005), 2, 57-72

Application of plasma-system for pulverized coal ignition and combustion stabilization in utility boiler furnaces promises to achieve certain savings compared to the use of heavy oil burners. Plasma torches are built in air-coal dust mixture ducts between coal mills and burners. Characteristics of processes in the ducts with plasma-system for pulverized coal combustion stabilization are analyzed in the paper, with respect to the modeling and numerical simulation of mass, momentum and heat transfer in two-phase turbulent gas-particle flow. The simulations have been performed for three different geometries of the air-coal dust mixture ducts with plasma torches, for TENTA1 utility boiler and pulverized lignite Kolubara-Field "D". Selected results of numerical simulation of processes are presented. The plasma-system thermal effect is discussed regarding corresponding savings of liquid fuel. The results of numerical simulations have been analyzed with respect to the processes in the duct and especially with respect to the influence of the duct shape to a temperature field at the outlet cross section, as a basis for the duct geometry optimization. It has been emphasized that numerical simulation of processes can be applied in analysis and optimization of pulverized coal ignition and combustion stabilization and enables efficient and cost-effective scaling-up procedure from laboratory to industrial level.

Key words: *modeling, pulverized coal, combustion stabilization, plasma, optimization*

Introduction

Pulverized coal ignition and combustion stabilization by means of plasma-chemical preparation of pulverized coal in utility boilers air-coal dust mixture ducts promise to achieve certain savings of liquid fuel. Due to the coal quality fluctuations during utility boilers operation, a need for heavy oil for boiler start up and pulverized coal combustion stabilization in domestic power plants is increased. Pulverized coal combustion stabilization is necessary also in the case of high-quality coal during reduced loading of steam boiler. Low temperature level in the furnace during burning of low-quality coal or at reduced boiler capacity, as well as an intensive cooling of furnace, make a spontaneous reaction of combustion impossible. It is necessary to introduce addi-

tional thermal energy into the system in order to provide continual combustion. During 1997, Serbian power plants consumed about 106,000 tons of liquid fuel, *i. e.* 55,000 tons for boilers start up and 51,000 tons for pulverized coal combustion stabilization [1], which corresponds to 1-2% of total coal consumption, while specific consumption of liquid fuel was 4 kg per MWh of electric energy. The solution to the problem can be found in the application of low-temperature air-plasma for the plasma-chemical preparation of pulverized coal. This process can be performed in ducts that conduct the mixture of air-coal dust in a utility boiler. The plasma-system for pulverized coal ignition and combustion stabilization is based on substitution of heavy oil by pulverized coal itself, being subjected to a thermo-chemical preparation, initiated by air-plasma, produced by plasma torches, built within the ducts between coal mills and burners.

Plasma thermal energy is used for heating the air-coal dust mixture and initiating additional thermal energy release due to the pulverized coal combustion, which contributes to a decrease of the plasma torches power required. While gasification of coal particles with carbon-dioxide and water vapor consumes energy, combustion of coal and gasification products, simultaneously releasing energy, should compensate energy losses and increase the thermal energy level of two-phase mixture in the duct. Limiting factors of the process are coal particles heating rate, relatively short residence time of the air-coal dust mixture in the duct and the fact that plasma effects only a part of the duct cross section (the flame propagation problem). Numerical simulation should give the suggestions for optimization of the parameters within design concept and thermo-flow characteristics of the facility and the process.

There are zones of intensive reactions due to the plasma effect as well as a relatively inert regions in which influence of colder air-coal dust mixture stream is predominant, giving a nonuniform temperature and concentration field in the duct. In such a situation, an over-domain averaging procedure, like in standard, engineering calculations, leads to the wrong conclusions. Conventional, empirical techniques of calculations do not provide reliability while treating changed operating conditions. A need for development of mathematical models exists also for the purpose of minimization of expensive and, often, incomplete experimental investigations. Simulations give complete fields of relevant variables in the domain as well as an in-depth understanding of complex processes in energy systems, providing information on the processes that cannot be obtained in any other way, as a basis for the process and system optimization.

A model developed and described in the paper is based on solving the partial differential equations of mass, momentum and energy conservation in reacting, two-phase turbulent flow, with using of additional relations describing different phenomena in the process and their mutual interactions. Numerical procedure is developed to the level in which it provides stable and reliable solutions.

A process of plasma-chemical preparation of pulverized coal takes place in sub-stoichiometric conditions (with oxygen mass concentration less than 10%) in which gasification of coal and combustion of gaseous products of gasification (in regions where the oxygen has not been consumed) are expected to be the dominant reactions. These phenomena are included in the model of reaction processes within a preparation of primary air and pulverized coal mixture. While a number of authors have already paid their

attention to the investigation of coal gasification [2-5], modeling and simulation of these processes [6] are considerably less often represented in literature. Processes of plasma thermo chemical treatment of coal at coal-fired thermal power stations [7-9] as well as mathematical modeling of plasma-chemical coal conversion processes (*e. g.* [10-12]) have been also investigated from various points of view. However, we could not have reached, through available references, the other authors' simulations results (if any) considering processes in air-coal dust mixture ducts in existing operating conditions at thermal power plants.

As the first step, a two-dimensional model for description of processes in axysymmetric and rectangular air-coal dust mixture ducts has been developed and verified. However, considering the duct geometry and dimensions, as well as the fact that intensive processes takes place only in some regions of the duct cross section and regarding considerable gradients of variables in transversal directions, the process occurring in the duct is considered to be a three-dimensional by its nature. A two-dimensional model gives approximately real picture of process only in the plane crossing the plasma torches axes, while pictures in other planes are considerably different. An appropriate description of global process can be obtained only by means of complete, three-dimensional simulations. On the base of two-dimensional model, a three-dimensional model has been developed as well as corresponding computer code for simulation of complex processes in the air-coal dust mixture ducts with plasma-system for combustion stabilization. The model takes into account the transfer of mass, momentum and energy between transport fluid, coal particles and plasma jet injected into the duct. Developed mathematical model has been verified and corresponding predictions compared with situations of different problems (pulverized coal flame, utility boiler furnace [13,14]). It has been applied here for the prediction of the process that has not been experimentally investigated, so there are no available referent experimental data. The model has been applied for simulation of processes in one of the air-coal dust mixture ducts with two opposite plasma torches, for TENT-A1 210 MW_e utility boiler firing pulverized Serbian Kolubara lignite, but for three different shapes of the duct: rectangular duct with constant cross section area, circular duct and rectangular duct with flow expansion through a diffuser. Selected results of numerical simulations are presented and analyzed with respect to the characteristics of processes and the thermal effect of plasma torches. A duct geometry influence to a temperature field in the outlet section of the duct is considered especially, providing a reliable approach for optimization of the duct geometry.

Mathematical model of plasma thermal and chemical preparation of coal in air-coal dust mixture duct

A three-dimensional elliptic flow is described by the model, with the main characteristics given in the paper. Axial flow of air-coal dust mixture through the duct, with lateral introduction of plasma jet is considered. Turbulent flow of multicomponent gaseous phase is treated in Eulerian field, eq. (1), for general variable Φ :

$$\frac{\partial}{\partial x_j}(\rho U_j \Phi) - \frac{\partial}{\partial x_j} \Gamma_\Phi \frac{\partial \Phi}{\partial x_j} = S_\Phi - S_p^\Phi \quad (1)$$

System of eq. (1) is closed by means of standard $k-\varepsilon$ gas turbulence model. Equation (1) is solved for mass, momentum, energy, gas components concentrations and turbulence kinetic energy and its dissipation. For coupling of gaseous and dispersed phase PSI-CELL (Particle Source in Cell) method is used, where additional sources due to particles S_p^Φ , obtained by particle tracking are introduced in eq. (1).

Radiation heat transfer is described by using the “model of six fluxes” [15]. Equations for total radiation fluxes are solved simultaneously with fluid dynamic equations by the same numerical procedure. In “x” direction, the equation is:

$$\frac{1}{K_t} \frac{d}{dx} \Gamma_{rd} \frac{dF_x}{dx} = (1 - \Omega_0 f - \Omega_0 b) F_x - 2\Omega_0 s (F_y - F_z) - (1 - \Omega_0) \frac{I_b}{3} \quad (2)$$

In eq. (2) $\Omega_0 = K_s / K_t$ is albedo of radiation scattering, while $K_t = K_a + K_s$ is total coefficient of radiation, as a sum of absorption and scattering coefficients. Equation (2) has equivalent form for the other two directions.

Dispersed phase is described by differential equations of motion, energy and mass change due to chemical reactions, in Lagrangian field, for individual particles, with diffusion model of particle dispersion by gas turbulence. Particle total velocity is a sum of convective and diffusion velocity:

$$\vec{U}_p = \vec{U}_{pc} + \vec{U}_{pd} \quad (3)$$

where convective velocity is obtained from the equation of particle motion and particle diffusion velocity is given as:

$$\vec{U}_{pd} = \frac{1}{N_p} \Gamma_p N_p, \quad U_{pdi} = \frac{1}{N_p} \Gamma_p \frac{\partial N_p}{\partial x_i} \quad (4)$$

where N_p is particle concentration (particle number density), constant along each particle trajectory, obtained from transport equation similar to eq. (1) and Γ_p is coefficient of particle turbulent diffusion:

$$\Gamma_p = \frac{v_p^t}{\sigma_p}, \quad v_p^t = v_t \left(1 + \frac{\tau_p}{\tau_t} \right)^{-1} \quad (5)$$

given with respect to the fluid and particles turbulent diffusivity, v_t and v_p^t .

Reactions model considers both heterogeneous and homogeneous chemical reactions.

Model of dispersed phase combustion and gasification

Heterogeneous reactions are described in combined kinetic-diffusion regime, within a “shrinking core” concept [16]. Reactions of oxidation of carbon and hydrogen from coal are considered directly, while sulfur is taken into account through equivalent carbon content. Kinetic parameters are taken from previous experimental investigations of Serbian lignites. Two reactions of coal combustion ($C + O_2 = CO_2$, $2H_2 + O_2 = 2H_2O$) and two of coal gasification ($C + H_2O = CO + H_2$, $C + CO_2 = 2CO$) are considered. Moisture evaporation from coal particles and consumption of coal originating oxygen are also taken into account. Pulverized coal particle reaction rate in combined kinetic-diffusion regime [16] is given as:

$$\frac{dm_p}{d\tau} = \mathcal{R}_p \frac{A_p M_p \chi_{mol}^{ox}}{\frac{1}{k_r} \frac{1}{k_d}} \quad (6)$$

where k_r is reaction rate parameter in kinetic regime, given by Arrhenius expression, eq. (7), and k_d is diffusion parameter of mass transfer, eq. (8):

$$k_r = A e^{-\frac{E}{RT}} \quad (7)$$

where A is pre-exponential factor and E activation energy, determined experimentally for coal considered. Parameter k_d is given as a function of Sherwood number Sh :

$$k_d = Sh \frac{\mathcal{D}}{d_p} \quad (8)$$

Molecular diffusivity \mathcal{D} is given by empirical expression for high-temperature combustion products [17]:

$$\mathcal{D} = 9.8 \cdot 10^{-10} T^{1.75} \quad (9)$$

Model of combustion in gaseous phase

Model describes combustion of carbon-monoxide ($2CO + O_2 = 2CO_2$) and hydrogen ($2H_2 + O_2 = 2H_2O$) in gas mixture, with solving the conservation equations, in the form of eq. (1), for components of the gas mixture: N_2 , O_2 , CO_2 , H_2O , CO , and H_2 . Homogeneous combustion process is controlled by slower of two processes: chemical kinetics and turbulent mixing:

$$\dot{\Omega}_c = \min(\dot{\Omega}_{ch}, \dot{\Omega}_{ct}) \quad (10)$$

Kinetic rate of oxidation reaction is given by Arrhenius expression:

$$\dot{\Omega}_{ch} = A_h \chi_{fu}^a \chi_{ox}^b \rho^c e^{-\frac{E_h}{RT}} \quad (11)$$

In addition to chemical kinetics, the second controlling mechanism is turbulent diffusion, *i. e.* turbulent mixing, which has been determined according to the “Eddy-Break-Up Model” [18]:

$$\dot{\Omega}_{ct} = A_{fu} \min \left(\rho \chi_{fu} \frac{\varepsilon}{k}, \rho \frac{\chi_{ox}}{s} \frac{\varepsilon}{k} \right) \quad (12)$$

For coefficient A_{fu} a value of 0.53 has been applied, as a universal value, often used.

Thermodynamic and transport properties are determined with respect to the equations of state, semiempirical relations and regressions of tabular data. Boundary conditions at the inlet are defined by the nature of the problem and at the outlet by the condition of continuity. Conditions near the walls are described by so called “wall functions”

Discretization of the gas phase partial differential equations has been performed by means of the control volume method and hybrid differencing scheme [19], according to a TEACH code for pure hydrodynamics [20], extended here for two-phase flow. Coupling of continuity and momentum equations are performed by SIMPLE algorithm [19] and stabilization of iteration by under-relaxation. Equations are solved by using SIPSOL method, derived from SIM procedure [21].

3D numerical grids have been used for calculations: with 76,500 nodes for the straight rectangular duct (for the reason of symmetry, a half of the duct is considered), with 73,696 nodes for the circular duct and with 156,604 nodes for the half of the duct with a diffuser, all giving a good convergence. In order to perform the grid refinement tests, different grid refinements have been also considered, for each of these cases. For the straight duct, additional grid with 147,900 nodes has been used. For circular duct, additional grid with 80,892 nodes has been used. For the duct with a diffuser, additional grids with 80,892, 92,684, and 182,172 nodes have been used. All numerical grids used, have given a good convergence, without any considerable difference in results. The analysis of the results, obtained in the cases considered, has not shown any important influence of numerical diffusion. Calculations have also emphasized the importance of numerical particles tracking for general solution convergence. Total number of 2100 trajectories has been considered in the predictions.

Problem description, calculation parameters and operation regime considered

Through the air-coal dust mixture duct, pulverized coal is carried by a transport fluid with following characteristics: mass flow rate 5.3 kg/s per duct (135,000 m³/h, *i. e.* 42.44 kg/s per one coal mill with 8 rectangular or 16 circular ducts going to the furnace), inlet temperature of mixture 170 °C and inlet composition of transport fluid (mass concentrations of components): $X_{CO_2} = 0.108$; $X_{H_2O} = 0.232$; $X_{N_2} = 0.574$; $X_{O_2} = 0.086$ (corresponding to the air-excess of 0.5). Pulverized coal mass flow rate corresponds to reduced grinding capacity 45 t/h of the mill (with nominal capacity of 68 t/h). Near the air-coal dust mixture inlet, from two opposite plasma torches at lateral sides of the duct,

air plasma jets enter the duct. Plasma mass flow rate is 0.015 kg/s per one torch (corresponding to the power of 100 kW per one torch, *i. e.* 200 kW for pair of torches, applied in one duct), inlet velocity 50 m/s and temperature 5000 K. Dimensions of the duct cross section for different duct shapes are given in tab. 1. Due to a plane-symmetry, only a half of rectangular ducts measuring 1.23 m in “y” direction is considered in the model. In the case of circular shape, the whole duct has been considered, because the plasma jet inlet is only at one side of the duct. Numerical simulation for all of the ducts have been done for the duct maximal length of 11.0 m.

Grinding fineness of pulverized coal is defined by five fractions of coal particles: 7.5% 0-50 μm , 18.6% 50-90 μm , 31.4% 90-200 μm , 25.1% 200-500 μm , and 17.3% >500 μm . Pulverized coal proximate analysis: moisture content 10.0%, combustible 54.0%, ash content 36.0%, total sulfur 0.7%, and lower heating value 12,903 kJ/kg. Pulverized coal ultimate analysis: carbon 33.06%, hydrogen 3.06%, sulfur (combustible) 0.443%, nitrogen 0.89%, and oxygen 16.54%. Pulverized coal composition and heating value are calculated according to assumption that moisture content of pulverized coal in the duct is 10%.

Table 1. Shape and dimensions of the air-coal dust mixture ducts considered

Air-coal dust mixture duct shape	Rectangular duct with constant cross section area	Circular duct	Rectangular duct with 1.7 m long diffuser
Dimensions of the duct cross section	1.23 0.26 m	diameter 0.480 m	1.23 0.26 m expanding by the diffuser to 1.23 0.535 m

Results and discussion

Numerical simulation, based on mathematical models of processes in air-coal dust mixture ducts, gives different information on the processes that cannot be obtained in any other way. As an illustration of the processes in a duct, numerical results for gas temperature field in characteristic sections of rectangular duct with constant cross section area are shown in figs. 1 and 2. Due to a symmetry with respect to $y = 0$ plane, fields are presented for the half of the duct only. Figure 1 presents gas temperature field in horizontal plane through the inlet of plasma-jet, while fig. 2 gives temperature field in perpendicular sections.

High-temperature air-plasma initiates the reactions of complete and partial oxidation of pulverized coal combustible components in the air-coal dust mixture ducts. There are local high temperatures (in very narrow zone up to 3500 K), originating from plasma-jet and intensive combustion in the region. Considerable mass flow rate of air-coal dust mixture blows the zone of plasma influence off in downstream direction and

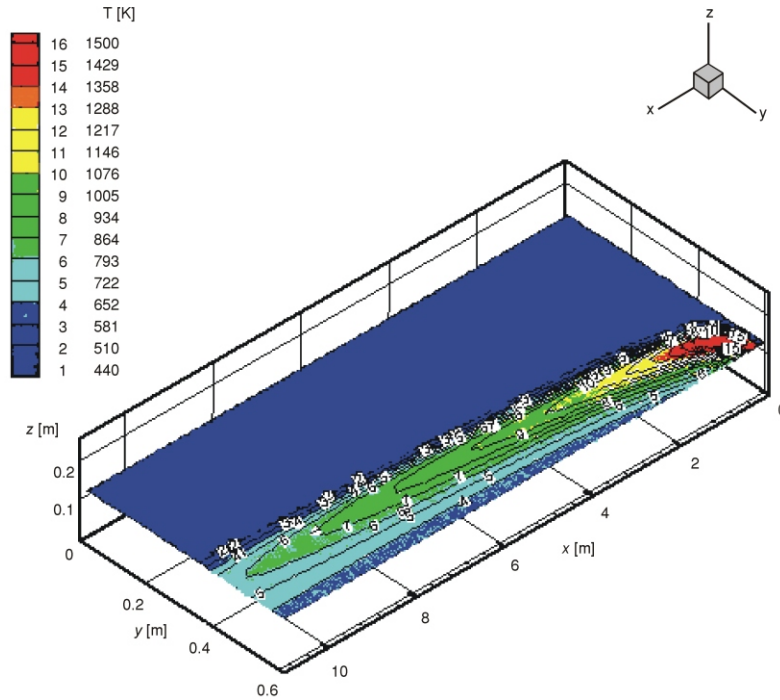


Figure 1. Gas temperature field in the rectangular duct with constant cross section area, in the plane through the plasma-jet inlet

may cause the extinction of flame. Air coal dust mixture mass flow rate is almost two hundred times higher than the plasma flow rate, so the effect of the plasma extreme temperatures to the thermal conditions in the duct decrease rapidly with lateral distance from the plasma-jet inlet, fig. 1. Dimensions of the duct cross section are for the order of magnitude greater than plasma-jet dimensions. Flame front velocity in lateral direction is considerably less than axial velocity of air-coal dust mixture flow, so the plasma influence is restricted to the narrow part of the duct. For the same reason, downstream spreading of reaction zone is relatively insignificant, figs. 1 and 2. Large amount of colder air-coal dust mixture stream makes lateral diffusion intensive, which additionally reduces the reaction zone width. Thus, there are zones of intensive reactions (high temperature regions) due to the plasma effect and wide, relatively inert field in the duct, fig. 2.

The coal gasification reactions are endothermic, consuming a portion of plasma thermal energy as well as energy originating from exothermic reactions of combustion. If gasification reactions would continue to the end, as well as without considerable consuming of produced gases, gasification reactions would be of the highest relative importance in the duct. Because of relatively short pulverized coal particles residence time in the duct, coal burning rate and corresponding consumption of oxygen from the gas are small

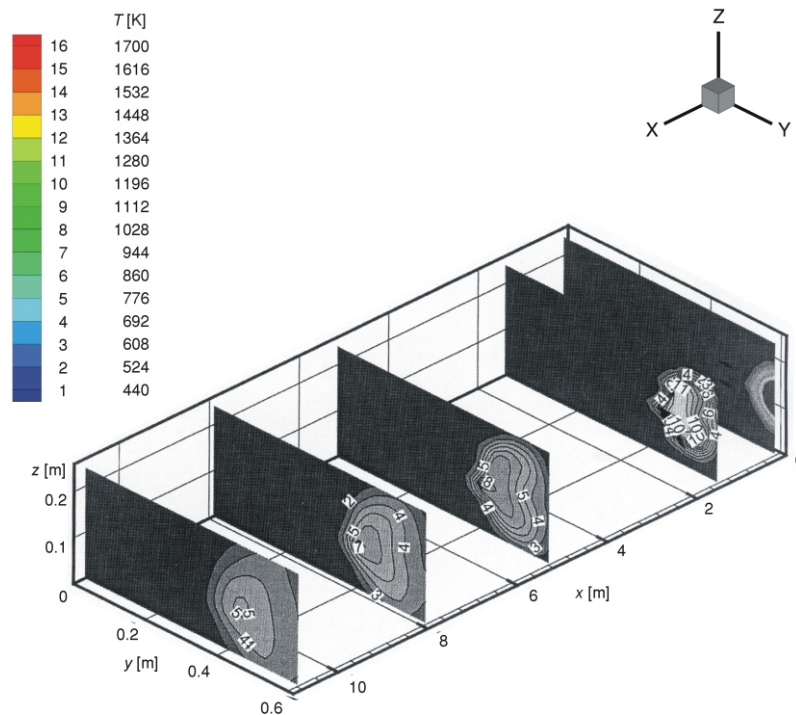


Figure 2. Gas temperature field in characteristic cross sections of the rectangular duct with constant cross section area

and there are no sub-stoichiometric conditions necessary for complete coal gasification. Gasification products flow from the region near plasma jet, in which they are produced, to a downstream zone, rich of unconsumed oxygen where there is a rapid combustion of carbon monoxide and hydrogen, giving a very small concentration of combustible gases at the duct outlet [22]. Described processes continue and the steady state is rapidly reached, with the level of gas thermal energy at the inlet into the furnace necessary for successful pulverized coal ignition and continual combustion.

It is important to find out to what extent the plasma torches increase a level of thermal energy in the duct for the purpose of substitution of heavy oil burners. Plasma thermal energy is used for heating the gases and pulverized coal mixture, while gasification also requires energy. Combustion of coal and gasification products produces thermal energy that should compensate these energy losses and increase thermal energy of the mixture. Thermal energy of air-coal dust mixture entering the duct (1 MW) is a sum of thermal energies of the mixture transport fluid and pulverized coal particles. Plasma-jets thermal energy corresponds to the power of a pair of plasma torches (in this case 0.2 MW). Energy output of the duct per time unit is a sum of gas and particles thermal energy and chemical energy of unburned gaseous products of gasification. Thermal effect of

plasma torches might be defined as a difference between energy output and energy of air-coal dust mixture entering the duct. In the case of rectangular duct with constant cross section area, the model predicts the energy per time unit 1.725 MW, providing the thermal effect of plasma torches pair equal to 0.755 MW per one duct, *i. e.* 6.0 MW for one pulverized coal burner with eight air-coal dust mixture ducts.

These considerations can also help in evaluation of plasma torches power required to replace heavy oil burners. The plasma-system thermal effect can be discussed also regarding corresponding savings of liquid fuel, but it is always necessary to consider existing operating conditions in the ducts and liquid fuel burners operation regime. For example, TENT-A1 210 MW_e utility boiler with six pulverized coal burners, applies heavy oil burners for boiler start up and pulverized coal combustion stabilization. Each unit is equipped with system of six heavy oil burners, with maximal capacity 2.5 t/h of each and heating value of heavy oil 39,550 kJ/kg [1]. The number of heavy oil burners to switch-on depends on the unit operation regime. Combustion stabilization is done by using two heavy oil burners in most cases (approximately 50%) and by using four burners only in 10% of cases. Only one burner is used in 25% of cases. Heavy oil burners participate with 9-14% in total thermal power of the unit (power of heavy oil burners and pulverized coal burners). In design of plasma-system for reliable pulverized coal ignition

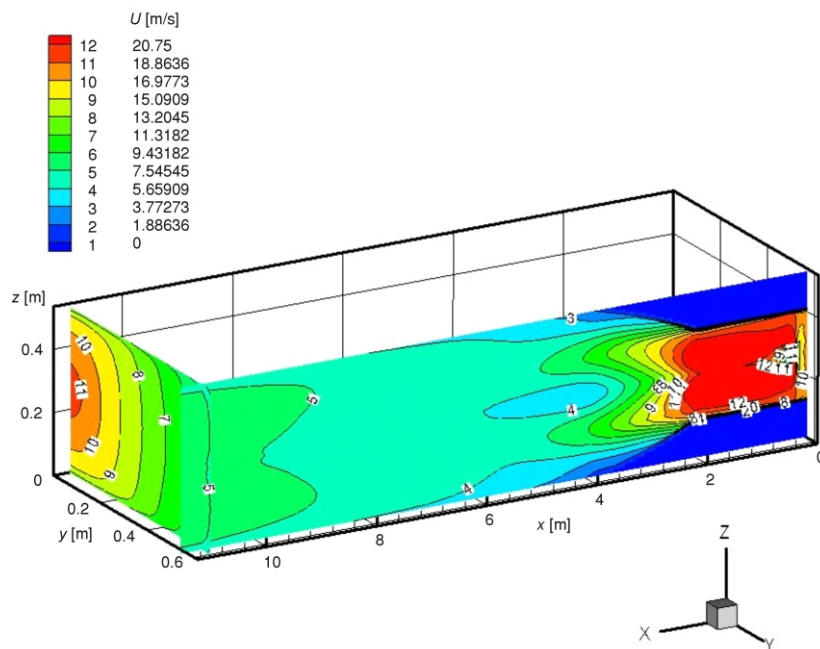


Figure 3. Gas axial velocity in characteristic sections of the rectangular duct with diffuser

and combustion stabilization, it is recommended to provide certain reserve of power. Potential savings of liquid fuel might be evaluated with respect to the fact that average annual liquid fuel consumption for these purposes in Electric Power Industry of Serbia is 80,000 tons [1].

In order to demonstrate the applicability of numerical simulation in optimization of the duct geometry, parametric calculations have been done for three different shapes of the duct: rectangular duct with constant cross section area, circular duct and rectangular duct with diffuser (fig. 3), with the rest of operating conditions being the same. As an indicator of the duct geometry influence to the duct processes, gas temperature field in the duct outlet cross section has been analyzed, fig. 4. Only the half of the rectangular ducts has been given, for the sake of a geometrical as well as flow field symmetry (with $y = 0$ plane of symmetry). The whole circular duct is given because the plasma jet intakes only at one side of the duct. Since the burning gases concentration at the duct outlet is small, as already explained, temperature of the gases in the outlet cross section is a measure for the thermal energy output, thus characterizing also the thermal effect of plasma torches. Figure 4 suggests that there is maximal energy effect

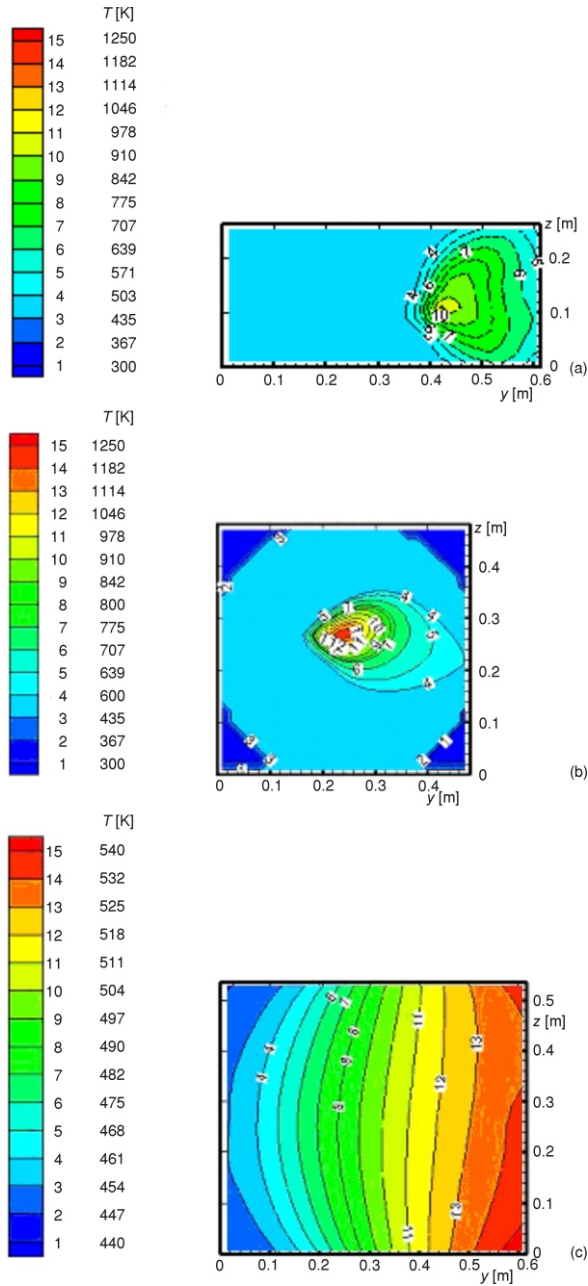


Figure 4. Gas temperature field in the duct outlet section, for different duct geometries
 (a) rectangular duct with constant cross section area, (b) circular duct, (c) rectangular duct with diffuser

of the processes in the duct initiated by the plasma jet, in the case of circular duct, while the minimal one is in the case of the duct with diffuser. The latter could be explained by a sudden decrease of the gas temperature due to an expansion through the diffuser, fig. 3, making the conditions for reactions become considerably worse, especially in this case where there is small oxygen concentration in the field [22].

It is necessary to emphasize that all the conclusions exposed in the paper relate to the operating conditions considered and that one should be always very careful when trying to generalize the conclusions because this requires analysis of quite a number of different operation regimes.

Conclusions

For the purpose of achieving the savings of liquid fuel, instead of usual system for pulverized coal ignition and combustion stabilization by heavy oil burners, plasma torches are built in air-coal dust mixture ducts of utility boiler furnaces. Paper presents characteristics and selected results of three-dimensional differential mathematical model developed for numerical simulations of flow, heat transfer and chemical reaction processes in the duct with plasma-system for pulverized coal ignition and combustion stabilization. Simulations have been performed for one of the air-coal dust mixture ducts with two opposite plasma torches, for 210 MW_e utility boiler unit firing pulverized Serbian Kolubara lignite. Results of the predictions suggest the importance of mass flow rate of extremely hot air-plasma and, especially, mass flow rate of much colder air-coal dust mixture, strongly influencing the processes in the duct. Numerical results are analyzed with respect to the thermal effect of plasma torches as well, that can be discussed also regarding corresponding savings of liquid fuel. However, for drawing the conclusions, it would be necessary to consider existing operating conditions in the ducts and liquid fuel burners operation regime in every case of interest. In order to demonstrate the applicability of numerical simulation in optimization of the duct geometry, parametric calculations have been done for three different shapes of the duct: rectangular duct with constant cross section area, circular duct and rectangular duct with diffuser, with the rest of operating conditions being the same. Temperature field in the duct outlet cross section has been analyzed. Numerical results suggests that, at the operating conditions considered, there is maximal energy effect of the processes in the duct initiated by the plasma jet, in the case of circular duct.

The aim of the paper has not been to suggest the solutions for some practical situations, but to present the predictive ability of the developed model, which gives the data that can be used as a basis to draw conclusions for considered situations. In general, results of simulations strongly depend on operating conditions. One should be very careful trying to generalize the conclusions, for this requires analysis of quite a number of different operation regimes. For final conclusions on the process performances and for the purpose of the process optimization, it is necessary to perform a series of numerical simulations by using this numerical algorithm. Simulation of processes, based on the submodels verified with respect to the laboratory measurements, can be successfully applied in anal-

ysis and optimization of pulverized coal ignition and combustion stabilization processes, as well as in determination of the plasma torches power required. It enables efficient and cost-effective scaling-up procedure from laboratory to industrial level and can reduce expences and development period for the corresponding pilot installations.

Acknowledgments

This work has been supported by the Ministry of Science and Environmental Protection (Republic of Serbia), within the project TR-147.

Nomenclature

A	– parameter in Arrhenius relation, [ms^{-1}]
A_{fu}	– coefficient for homogeneous reaction, [–]
A_{h}	– parameter in Arrhenius relation for homogeneous reaction, [$\text{kgm}^{-3}\text{s}^{-1}$]
A_{p}	– particle cross section area, [m^2]
a, b, c	– coefficients of homogeneous reaction, [–]
\mathcal{D}	– molecular diffusivity, [m^2s^{-1}]
d_{p}	– particle diameter, [m]
E	– activation energy of coal, [Jkmol^{-1}]
E_{h}	– homogeneous reaction activation energy, [Jkmol^{-1}]
F_x, F_y, F_z	– total radiation flux components, [Wm^{-2}]
f, b, s	– scattering direction coefficients, [–]
I_{b}	– black body radiation intensity, [Wm^{-2}]
K_{t}	– total coefficient of radiation, [m^{-1}]
$K_{\text{a}}, K_{\text{s}}$	– absorption and scattering coefficient, [m^{-1}]
k	– turbulence kinetic energy, [m^2s^{-2}]
k_{r}	– kinetic reaction rate, [ms^{-1}]
k_{d}	– diffusion reaction rate, [ms^{-1}]
M	– molar mass, [kgmol^{-1}]
m_{p}	– particle mass, [kg]
N_{p}	– particle concentration (number density), [m^{-3}]
R	– universal gas constant, [$\text{Jkmol}^{-1}\text{K}^{-1}$]
\mathcal{R}_{p}	– heterogeneous reaction rate, [kgs^{-1}]
Sh	– Sherwood number, [–]
S_{Φ}	– source term of general variable Φ
S_{p}^{Φ}	– additional source due to particles
s	– stoichiometric coefficient, [–]
T	– temperature, [K]
U_j	– time-averaged velocity component, [ms^{-1}]
\vec{U}	– particle total velocity vector, [ms^{-1}]
$\vec{U}_{\text{pc}}, \vec{U}_{\text{pd}}$	– particle convective and diffusion velocity vector, [ms^{-1}]
U_{pd_i}	– particle diffusion velocity component, [ms^{-1}]
x_j	– coordinate in general index-notation, [m]
x, y, z	– Cartesian coordinates, [m]

Greek letters

Γ_p	– particle turbulent diffusion coefficient, [m^2s^{-1}]
Γ_{rd}	– radiation diffusion coefficient, [m]
Γ_Φ	– transport coefficient for general variable Φ
ε	– turbulence kinetic energy dissipation, [m^2s^{-3}]
ν_p^t	– particles turbulent diffusivity, [m^2s^{-1}]
ν_i	– fluid turbulent diffusivity, [m^2s^{-1}]
ρ	– density, [kgm^{-3}]
σ_p	– Prandtl-Schmidt number for particles, [–]
τ	– time, [s]
τ_p	– particle response time, [s]
τ_i	– gas phase Lagrangian integral time scale, [s]
Φ	– general variable
χ_{mol}^{ox}	– oxidant molar concentration, [$kmolm^{-3}$]
χ_{fu}, χ_{ox}	– mass concentrations of combustible gas and oxidant, [$kgkg^{-1}$]
Ω_0	– albedo of radiation scattering, [–]
Ω_c	– homogeneous reaction rate, [$kgm^{-3}s^{-1}$]
Ω_{ch}, Ω_{ct}	– kinetic and turbulent mixing reaction rates of homogeneous reaction, [$kgm^{-3}s^{-1}$]

Subscripts

d	– diffusion
fu	– fuel (combustible gas)
h	– homogeneous reaction
mol	– molar
ox	– oxidant
p	– particle
r	– radiation
s	– scattering
t	– turbulent; total
x, y, z	– directions along Cartesian coordinates
Φ	– related to a general variable Φ

Superscripts

a, b, c	– coefficients of homogeneous reaction, [–]
ox	– oxidant
t	– turbulent
Φ	– related to a general variable Φ

References

- [1] Pavlović, P., Stefanović, P., Application of Plasma Torches for Combustion Stabilization in 210 MW Utility Boiler of Nikola Tesla Thermal Power Plant (in Serbian), A Study Report, VINČA Institute of Nuclear Sciences, Belgrade, 1999
- [2] Qiu, J., *et al.*, Coal Gasification in Steam and Air Medium under Plasma Conditions: a Preliminary Study, *Fuel Processing Technology*, 85 (2004), pp. 969-982

- [3] Yang, K. L., Yang, R. T., Absolute Rate of the Carbon-Carbon Dioxide Reaction, *AIChE Journal*, 31 (1985), 8, pp.1313-1321
- [4] Johanson, J. L., Fundamentals of Coal Gasification, in: Chemistry of Coal Utilization, John Wiley Co., New York, 1981, pp. 1585-1586
- [5] Batchelde, H. R., Busche, R. M., Armstrong, W. P., Kinetics of Coal Gasification, *Industrial and Engineering Chemistry*, 45 (1953), 9, pp. 1856-1871
- [6] Vamvuka, D., Woodburn, E. T., Peter, R. Senior, Modelling of an Entrained Flow Coal Gasifier, *Fuel*, 74 (1995), 10, pp. 1452-1460
- [7] Sugimoto, M., *et al.*, Stabilization of Pulverized Coal Combustion by Plasma Assist, *Thin Solid Films*, 407 (2002), pp. 186-191
- [8] Karpenko, E. I., Messerle, V. E., Peregudov, V. S., Plasma Thermochemical Treatment of Coals for Reducing the Consumption of Fuel Oil at Coal-Fired Thermal Power Stations, *Thermal Engineering*, 49 (2002),1, pp. 25-28
- [9] Zhukov, M. F., Peregudov, V. S., Plasma Technology for Ignition in Coal-Dust-Fired Boilers (in Russian), *Teploenergetika*, 12 (1996), pp. 61-64
- [10] Messerle, A. V., Mathematical Simulation of Plasma-Chemical Coal Conversion, *High Energy Chemistry*, 38 (2004), 1, pp. 35-40
- [11] Tian, Y. *et al.*, Simulation of Coal Pyrolysis in Plasma Jet by CPD Model, *Energy and Fuels*, 15 (2001), 6, pp. 1354-1358
- [12] Karpenko, E. I. *et al.*, Comparative Analysis of Energetic Efficiency of Plasma and Fire Technologies of Ignition, Combustion and Gasification of Coal Dust Spray by Using Mathematical Modeling of Chemically Non-Equilibrium Systems (in Russian), *Teplofiz. Aeromekh.*, 3 (1995), 2, pp. 289-294
- [13] Belošević, S., Sijerčić, M., Oka, S., Brkić, Lj., Živanović, T., Simulation of the Pulverized Coal Utility Boiler Furnace Operating Condition (in Serbian), *Procesna tehnika*, 20 (2004), 2-3, pp. 191-195
- [14] Belošević, S., Contribution to the Modeling of Processes in Pulverized Coal Combustion Boiler Furnace (in Serbian), Ph. D. thesis, Faculty of Mechanical Engineering, University of Belgrade, 2003
- [15] Hottel, C. H., Sarofim, F. A., Radiative Transfer, McGraw Hill, New York, 1967
- [16] Smoot, L. D., Smith, P. J., Coal Combustion and Gasification, Plenum Press, New York, 1985
- [17] Vilenskij, T. V., Hemaljan, D. M., Dynamics of Pulverized Fuel Combustion (in Russian), Energiya, Moskow, 1978
- [18] Spalding, D. B., Development of the Eddy-Break-Up Model of Turbulent Combustion, *Proceedings*, 16th International Symposium on Combustion, Cambridge, MA, USA, August 15-20, 1976, pp. 1657-1663
- [19] Patankar, S. V., Numerical Heat and Fluid Flow, Hemisphere Publishing Corp., New York, 1980
- [20] Gosman, A. D., Ideriah, F. J. K., Guide to the TEACH-T Program, Report, Mechanical Engineering Dept., Imperial College, London, 1976
- [21] Perić, M., Scheurer, G., CAST – a Finite Volume Method for Prediction of Two-Dimensional Flow and Heat Transfer Phenomena, Report No. SRR-89-01, Garching, Germany, 1989
- [22] Sijerčić, M., Belošević, S., Stefanović, P., Modeling of Processes in Air-Coal Dust Mixture Ducts with Plasma System for Fire Start up (in Serbian), *Proceedings*, Symposium Power Plants 2004 with international participation, Vrnjačka Banja, Serbia and Montenegro, November 2-5, 2004 (in press)

Authors' address:

M. Sijerčić, S. Belošević, P. Stefanović
VINČA Institute of Nuclear Sciences
Laboratory for Thermal Engineering and Energy,
11001 Belgrade, P. O. Box 522, Serbia and Montenegro

Corresponding author (S. Belošević):
E-mail: v1belose@vin.bg.ac.yu

Paper submitted: March 18, 2005
Paper revised: April 19, 2005
Paper accepted: May 30, 2005