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A numerical study of pulverized coal ignition by means of plasma torches in air–coal dust mixture ducts of utility boiler furnaces

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Abstract

Paper presents selected results of numerical simulation of processes in air–coal dust mixture duct of pulverized coal utility boiler furnace with plasma-system for pulverized coal ignition and combustion stabilization. Application of the system in utility boiler furnaces promises to achieve important savings compared with the use of heavy oil burners. Plasma torches are built in air–coal dust mixture ducts between coal mills and burners. Calculations have been performed for one of rectangular air–coal dust mixture ducts with two opposite plasma torches, used in 210 MW_e utility boiler firing pulverized Serbian lignite. The simulations are based on a three-dimensional mathematical model of mass, momentum and heat transfer in reacting turbulent gas-particle flow, specially developed for the purpose. Characteristics of processes in the duct are analyzed in the paper, with respect to the numerical results. The plasma-system thermal effect is discussed as well, regarding corresponding savings of liquid fuel. It has been emphasized that numerical simulation of the processes can be applied in optimization of pulverized coal ignition and combustion stabilization and enables efficient and cost-effective scaling-up procedure from laboratory to industrial scale.

Keywords: Modeling; Pulverized coal; Ignition; Plasma torches; Utility boiler

1. 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 additional 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 of 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 the 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

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Nomenclature

A	parameter in Arrhenius relation (m s^{-1})
A_{fu}	coefficient for homogeneous reaction (–)
A_h	parameter in Arrhenius relation for homogeneous reaction (kg m^{-3} s^{-1})
A_p	particle cross section area (m^2)
a, b, c	coefficients of homogeneous reaction (–)
b, f, s	scattering direction coefficients (–)
C_p	specific heat (J kg^{-1} K^{-1})
C_μ	constant in the expression for μ_t (–)
$\mathscr{D}$	molecular diffusivity (m^2 s^{-1})
d	diameter (m)
E	activation energy of coal (J k mol^{-1}); constant in the log law of the wall (–)
E_h	homogeneous reaction activation energy (J k mol^{-1})
F	total radiation heat flux (W m^{-2})
G	turbulence kinetic energy production (kg m^{-1} s^{-3})
I	radiation intensity (W m^{-2})
J	radiation intensity (W m^{-2})
K	coefficient of radiation (m^{-1})
k	turbulence kinetic energy (m^2 s^{-2}); reaction rate (m s^{-1})
M	molar mass (kg mol^{-1})
m	mass (kg)
N_p	particle concentration (particle number density (m^{-3}))
q	heat flux (W m^{-2})
R	universal gas constant (J k mol^{-1} K^{-1})
Re_p	heterogeneous reaction rate (kg s^{-1})
r	surface reflectivity (–)
Sh	Sherwood number (–)
S_Φ	source term for general variable Φ
S_p^Φ	additional source due to particles
s	stoichiometric coefficient (–)
T	temperature (K)
T^+	non-dimensional temperature(–)
t	temperature (°C)
U^+	non-dimensional velocity(–)
U_e	time-averaged velocity at the position y_e (m s^{-1})
U_j	lime-averaged velocity component (m s^{-1})
U_p	particle velocity vector (m s^{-1})
U_{pdi}	particle diffusion velocity component (m s^{-1})
U_τ	"shear velocity" (m s^{-1})
V	volume (m^3)
XCO_2, XCO, XH_2O, XN_2, XO_2	mass concentrations of carbon-dioxide, carbon-monoxide, water vapor, nitrogen and oxygen, respectively (kg kg^{-1})
x_j	coordinate in general index-notation (m)
x, y, z	Cartesian coordinates (m)
y^+	non-dimensional coordinate (–)
y_e	distance from the wall to the center of the first control volume (m)

Greek symbols

Γ	diffusion coefficient (m^2 s^{-1})
Γ_{rd}	radiation diffusion coefficient (m)
Γ_Φ	transport coefficient for general variable Φ
ε	turbulence kinetic energy dissipation rate (m^2 s^{-3}); emissivity (–)
κ	von Karmann constant (–)
λ	thermal conductivity (W m^{-1} K^{-1})
μ	dynamic viscosity (kg m^{-1} s^{-1})
ν_p	particles turbulent diffusivity (m^2 s^{-1})
ν_f	fluid turbulent diffusivity (m^2 s^{-1})
ξ	coordinate in Lagrangian field (m)
ρ	density (kg m^{-3})
σ	Stefan–Boltzmann constant (W m^{-2} K^{-4})
σ_h	laminar Prandtl–Schmidt number for thermal energy (–)
$\sigma_{h,t}$	turbulent Prandtl–Schmidt number for thermal energy (–)
σ_p	Prandtl–Schmidt number for particles (–)
τ	time (s)
τ_p	particle response time (s)
τ_l	gas phase Lagrangian integral time scale (s)
τ_w	shear stress (N m^{-2})
Φ	general variable
χ_{mol}^{ox}	oxidant molar concentration (k mol m^{-3})
χ_{fu}, χ_{ox}	mass concentrations of combustible gas and oxidant (kg kg^{-1})
Ω_O	albedo of radiation scattering (–)
$\dot{\Omega}_e$	homogeneous reaction rate (kg m^{-3} s^{-1})
$\dot{\Omega}_{ch}, \dot{\Omega}_{ct}$	kinetic and turbulent mixing reaction rates of homogeneous reaction (kg m^{-3} s^{-1})

Subscripts

a	absorption
b	black body
c	convective
d	diffusion
fu	fuel (combustible gas)
h	homogeneous reaction; enthalpy
mol	molar
ox	oxidant
p	particle
r	radiation
s	scattering
t	turbulent; total
w	wall
x, y, z	related to 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

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 tune 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.

In the duct, 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 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. There is a need for development of mathematical models 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, using additional relations describing different phenomena in the process and their mutual interactions. Numerical procedure is developed to the level in which it provides stabile 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 air-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 thermochemical 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 also been 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 basis of the 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. Individual submodels of the comprehensive model have been verified and corresponding predictions compared with situations of different problems (pulverized coal flame, utility boiler furnace [13–15]). The developed model has been applied here for the prediction of processes that have 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 rectangular air–coal dust mixture ducts with two opposite plasma torches, for TENT-A1 210 MW_c utility boiler firing pulverized Serbian Kolubara lignite. Selected results of numerical simulations arc presented and analyzed with respect to the characteristics of processes. The thermal effect of the plasma torches is discussed as well, regarding corresponding savings of liquid fuel.

2. Geometry and operating conditions of the case-study air–coal dust mixture duct

The case-study boiler unit is 210 MW_e unit of Nikola Tesla power plant (Serbia), with eight jet burners each connected to one coal mill and having eight rectangular air–coal dust mixture ducts. Pulverized coal is carried through the duct by a transport fluid with following characteristics: mass flow rate 5.3 kg/s per duct, inlet temperature of mixture 170 °C and inlet composition of transport fluid (mass concentrations of components): $XCO_2 = 0.108$; $XH_2O = 0.232$; $XN_2 = 0.574$; $XO_2 = 0.086$ (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 rectangular duct with constant cross section area (1.23 × 0.26) m. Due to a plane-symmetry, only a half of the rectangular duct in "*y*" direction is considered in the model. Numerical simulation for the duct has 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, 17.3% (>500 μm). The pulverized coal (Kolubara Field "D") proximate analysis: moisture content 10.0%, combustible 54.0%, ash content. 36.0%. total sulfur 0.7%; and lower heating value 12903 kJ/kg. The pulverized coal ultimate analysis: carbon 33.06%, hydrogen 3.06%, sulfur (combustible) 0.443%, nitrogen 0.89% and oxygen 16.54%. The pulverized coal composition and heating value are determined for the moisture content of 10%.

3. Mathematical model and numerical method

A three-dimensional elliptic flow is described by a specially developed differential model, with the main characteristics given in the paper. The model offers such a composition of submodels and modeling approaches to balance submodel sophistication with computational practicality.

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 $\varPhi$

$$\frac{\partial}{\partial x_{\mathrm{j}}}(\rho U_{\mathrm{j}}\varPhi)=\frac{\partial}{\partial x_{\mathrm{j}}}\left(\varGamma_{\varPhi}\frac{\partial\varPhi}{\partial x_{\mathrm{j}}}\right)+S_{\varPhi}+S_{\mathrm{p}}^{\varPhi} \tag{1}$$

System of Eq. (1) is closed by means of standard k-ε gas turbulence model. Eq. (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 $S_{\mathrm{p}}^{\varPhi}$, obtained by particle tracking are introduced in Eq. (1).

Radiation heat transfer is described by using the "model of six fluxes" [16]. Equations for total radiation fluxes are solved simultaneously with fluid dynamic equations by the same numerical procedure. In "*x*" direction, the equation is

$$\frac{I}{K_{\mathrm{t}}}\frac{\mathrm{d}}{\mathrm{d}x}\left(\varGamma_{\mathrm{rd}}\frac{\mathrm{d}F_x}{\mathrm{d}x}\right)=-(I-\varOmega_0f-\varOmega_0b)F_x+2\varOmega_0s(F_y+F_z)+(I-\varOmega_0)\frac{I_b}{3} \tag{2}$$

In Eq. (2) $\varOmega_0=K_{\mathrm{s}}/K_{\mathrm{t}}$ is albedo of radiation scattering, while $K_{\mathrm{t}}=K_0+K_{\mathrm{s}}$ is total coefficient of radiation, as a sum of absorption and scattering coefficients. Eq. (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

$$\vec{U}_{\mathrm{p}}=\vec{U}_{\mathrm{pc}}+\vec{U}_{\mathrm{pd}} \tag{3}$$

The convective velocity is obtained from the equation of particle motion, by particle tracking along the trajectories with constant particle number density. The particle diffusion velocity is given as

$$\vec{U}_{\mathrm{pd}}=-\frac{1}{N_{\mathrm{p}}}\varGamma_{\mathrm{p}}\nabla N_{\mathrm{p}},U_{\mathrm{pd_i}}=-\frac{1}{N_{\mathrm{p}}}\varGamma_{\mathrm{p}}\frac{\partial N_{\mathrm{p}}}{\partial x_i} \tag{4}$$

where N_{p} is particle concentration (particle number density), obtained from the transport equation in the form of Eq. (1) and $\varGamma_{\mathrm{p}}$ is coefficient of particle turbulent diffusion

$$\varGamma_{\mathrm{p}}=\frac{v_{\mathrm{p}}^t}{\sigma_{\mathrm{p}}},v_{\mathrm{p}}^t=v_{\mathrm{t}}\cdot\left(1+\frac{\tau_{\mathrm{p}}}{\tau_{\mathrm{t}}}\right)^{-1} \tag{5}$$

given with respect to the fluid and particles turbulent diffusivity, v_{l} and v_{p}^t.

Both heterogeneous and homogeneous chemical reactions are considered in the model. Heterogeneous reactions are described in combined kinetic-diffusion regime, within a "shrinking core" concept [17]. 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 is also taken into account. Pulverized coal particle reaction rate in combined kinetic-diffusion regime [17] is given as

$$-\frac{\mathrm{d}m_{\mathrm{p}}}{\mathrm{d}\tau}=\mathscr{R}_{\mathrm{p}}=\frac{A_{\mathrm{p}}M_{\mathrm{p}}\chi_{\mathrm{mol}}^{\mathrm{ox}}}{\frac{I}{k_{\mathrm{r}}}+\frac{I}{k_{\mathrm{d}}}} \tag{6}$$

where k_{r} is reaction rate parametar in kinetic regime, given by Arrhenius expression, Eq. (7), and k_{d} is diffusion parameter of mass transfer. Eq. (8).

$$k_{\mathrm{r}}=\mathrm{A}\mathrm{e}^{-\frac{\mathrm{E}}{\mathrm{R}T}} \tag{7}$$

A is pre-exponential factor and E activation energy, determined experimentally for the coal considered. Parameter k_{d} is given as a function of Sherwood number S_{h}

$$k_{\mathrm{d}}=S_{\mathrm{h}}\cdot\mathscr{D}/d_{\mathrm{p}} \tag{8}$$

Molecular diffusivity $\mathscr{D}$ is given by empirical expression for high-temperature combustion products [18]

$$\mathscr{D}=9.8\times10^{-10}\cdot T^{1.75} \tag{9}$$

The submodel of reactions in gaseous phase 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. The applied calculation procedure allows, at reasonable computation time, taking into account by far more chemical components of the multicomponent gaseous mixture in the duct. However, we have limited the simulations to a model of reactions between six components that exert the most significant effect. In these considerations, we are interested also in the overall effects of the combination of combustion and gasification processes in the duct, with hydrogen and carbon-monoxide as the unburned combustible gases entering the furnace from the duct outlet. Regarding the substoichiometric conditions in the duct, we have investigated the influence of gasification in particular and found that most of the gasification products are combusted in downstream direction.

Homogeneous combustion process is controlled by slower of two processes: chemical kinetics and turbulent mixing.

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

Kinetic rate of oxidation reaction is given by Arrhenius expression

$$\dot{\Omega}_{\mathrm{ch}} = \mathrm{A_h} \cdot \chi_{\mathrm{f0}}^{\mathrm{a}} \cdot \chi_{\mathrm{ox}}^{\mathrm{b}} \rho^{\mathrm{c}} \cdot \mathrm{e}^{-\frac{\mathrm{E_h}}{\mathrm{R}T}} \tag{11}$$

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” [19]

$$\dot{\Omega}_{\mathrm{ct}} = \mathbf{A}_{\mathrm{fu}} \min\left[\rho \cdot \chi_{\mathrm{f}u} \cdot \frac{\varepsilon}{k}, \rho \cdot \frac{\chi_{\mathrm{ox}}}{\mathrm{s}} \cdot \frac{\varepsilon}{k}\right] \tag{12}$$

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

Initial and boundary conditions usual in modeling practice for elliptical partial differential equations are applied. Because of the application of Cartesian coordinates, caused by the overall geometry of the duct having rectangular cross section, there was no need for using the conditions of axial symmetry of the plasma stream. The approximation of the axisymmetrical plasma jet by the square one takes into account an existing mass flow rate of the plasma jet into the air–coal dust mixture duct.

The boundary conditions have been explained in our previous works, e.g., [20]. but they are summarized here as well. Boundary conditions at the inlet are defined by the nature of the problem and at the outlet by continuity. At the plane of symmetry, velocity components V, W and gradients of all the variables are set equal to zero. The near-wall conditions are described by so called “wall functions”. At the wall, the values of variables, flux or variables near the wall are defined. Velocity component perpendicular to the wall equals zero. For the velocity vector obtained by summing the parallel to the wall and the tangential velocity component, the wall shear stress is specified by expressions corresponding to the viscous and turbulent zones of the wall layer

$$\tau_{\mathrm{w}} = \begin{cases} \frac{\mu U_{\mathrm{e}}}{y_{\mathrm{e}}} & \text{for } y^+ < 11.63 \\ \frac{\kappa C_\mu^{1/4} \rho U_{\mathrm{e}} k^{1/2}}{\ln[\mathrm{E}y^+]} & \text{for } y^+ \geqslant 11.63 \end{cases} \tag{13}$$

The corresponding convection heat flux at the wall is

$$q_{\mathrm{w}} = \begin{cases} \frac{\mu C_{\mathrm{p}}}{\sigma_{\mathrm{h}}} \cdot \frac{T_{\mathrm{w}} - T}{y_{\mathrm{e}}}, & \text{for } y^+ < 11.63 \\ \frac{C_{\mathrm{p}} \rho C_\mu^{1/4} k^{1/2} (T_{\mathrm{w}} - T)}{T^+}, & \text{for } y^+ \geqslant 11.63 \end{cases} \tag{14}$$

The source of turbulent kinetic energy in the near wall region transforms into

$$\int (G - \rho\varepsilon) dV = \left(\frac{\tau_{\mathrm{w}} U_{\mathrm{e}}}{y_{\mathrm{e}}} - \frac{\rho \mathrm{C}_\mu^{3/4} k^{3/2} U^+}{y_{\mathrm{e}}}\right) \delta V. \tag{15}$$

while the turbulence energy dissipation is defined by

$$\varepsilon = \frac{C_\mu^{3/4} k^{3/2}}{\mathrm{K} y_{\mathrm{e}}} \tag{16}$$

The resulting non-dimensional velocity U^+ is derived in terms of the non-dimensional coordinate ($y^+ = U_\tau y_{\mathrm{e}}/v$)

$$U^+ = \frac{U}{U_\tau} = \frac{U}{(\tau_{\mathrm{w}}/\rho)^{1/2}} = \begin{cases} y^+ & \text{for } y^+ < 11.63 \\ \frac{1}{\kappa} \ln(\mathrm{E}y^+) & \text{for } y^+ \geqslant 11.63 \end{cases} \tag{17}$$

where y_{e} is the distance from the wall to the center of the first controle volume next to the wall and values of the other quantities pertain to that point.

The non-dimensional temperature at the center of the first controle cell next to the wall is defined by

$$T^+ = \begin{cases} \frac{C_{\mathrm{p}} \mu}{\lambda} y^+ = \sigma_{\mathrm{h}} y^+, & \text{for } y^+ < 11.63 \\ \sigma_{\mathrm{h}} \left\{ U^+ + 9.24[(\sigma_{\mathrm{h}}/\sigma_{\mathrm{h.t}})^{3/4} - 1] \right\}, & \text{for } y^+ \geqslant 11.63 \end{cases} \tag{18}$$

Thermal radiation flux at the wall is derived from $J = r_{\mathrm{w}} + \varepsilon_{\mathrm{w}} \sigma T_{\mathrm{w}}^4$, yielding

$$F_{\mathrm{w}} = (F - 2\varepsilon_{\mathrm{w}} \sigma T_{\mathrm{w}}^4 W_{\mathrm{h}})/[1 - (1 - r_{\mathrm{w}}) W_{\mathrm{h}}];$$
$$W_{\mathrm{h}} = -y_{\mathrm{e}}/[\Gamma_{\mathrm{rd}}(1 - r_{\mathrm{w}})] \tag{19}$$

The general form of dispersed phase equations in Lagrangian field is: $\mathrm{d}\xi/\mathrm{d}\tau = A - B\xi$, with the recurrent solution: $\xi_{\mathrm{n+1}} = \xi_n \mathrm{e}^{\mathrm{B}\Delta\tau} + A/B(1 - e^{\mathrm{B}\Delta\tau})$ and with the initial conditions defined by the solution from the proceeding time interval $\Delta\tau$. It is assumed that the particles colliding with the wall reflect with a given degree of elasticity. Condition at the plane of symmetry implies a fictitious “elastic reflection” of particles, meaning that every crossing of a particle through the plane corresponds to the back crossing of another particle from the opposite direction.

The gas phase thermodynamic and transport properties are determined with respect to the equations of state, semi-empirical relations and regressions of tabular data. Specific heat of panicle is given by empirical expression $C_{pp} = 832.2 + 0.489\ (T - 130)$.

Discretization of the gas phase partial differential equations has been performed by means of the control volume method and hybrid differencing scheme [21], according to a TEACH code for pure hydrodynamics [22], extended here for two-phase flow. Coupling of continuity and momentum equations are performed by SIMPLE algorithm [21] and stabilization of iteration procedure by under-relaxation. Equations are solved by using SIPSOL method, derived from SIP procedure [23].

A three-dimensional staggered, structured numerical grid has been used for the calculations. The grid with 104,550 grid nodes has been applied to provide the convergence and accuracy of the solutions and, in the same Lime, to meet the restrictions in computational time. In order to perform the grid refinement test, additional grid with 147,900 nodes has been used. Both numerical grids 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 particle trajectories has been considered in the predictions.

4. Results and discussion

Numerical simulation, based on mathematical model of processes in air–coal dust mixture ducts, gives different information on the processes that cannot be obtained in any other way. The model has been tested and verified by comparisons with measurements for simple, as well as complex test-cases, e.g. [13–15]. Moreover, some preliminary experimental investigations of the flow and temperature field in the TENT Al 210 MW_c power plant air–coal dust mixture ducts have been done recently, for the operating conditions quite similar to the ones numerically simulated within this work. The temperature of the multicomponent gas mixture has been measured by a thermoelement, placed at the spot 3m distant from the plasma jet inlet downstream and 0.1 m from the wall inside the duct. The predicted temperature of 705 °C corresponds to the measured value of 730 °C.

4.1. The numerical results characterizing plasma-chemical preparation of pulverized coal in air–coal dust mixture duct

As an illustration of the processes in the duct, numerical results for gas temperature field, as well as oxygen and carbon-monoxide concentration fields in a characteristic section of the rectangular duct are shown in Figs. 1–3. Due to a symmetry with respect to $y = 0$ plane, fields are presented for the half of the duct only.

Fig. 1 presents gas temperature field in horizontal plane through the inlet of plasma-jet. 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 tempera-

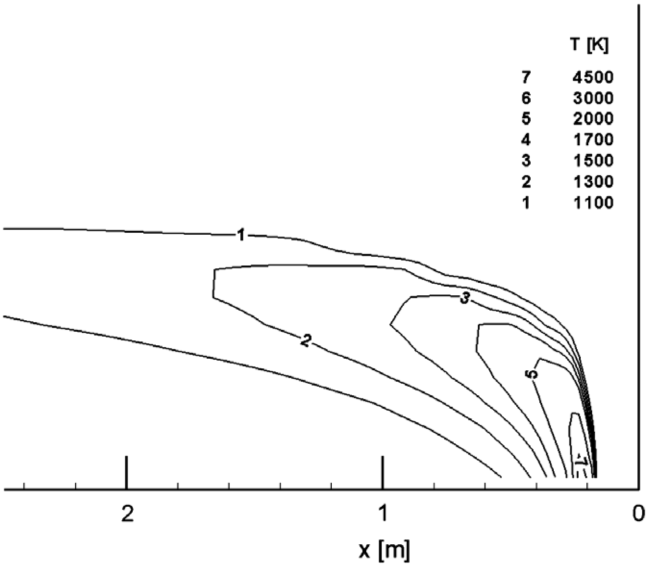

Fig. 2. Local gas temperature near the plasma jet inlet.

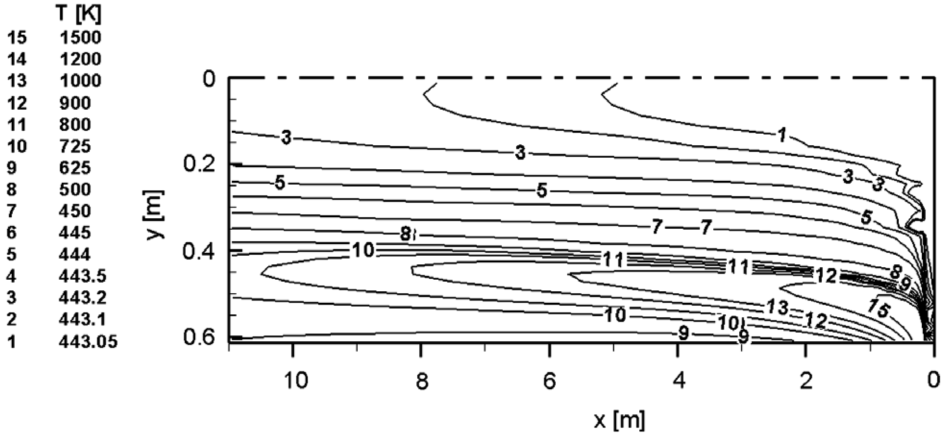

Fig. 1. Gas temperature in the horizontal plane through the plasma-jet inlet.

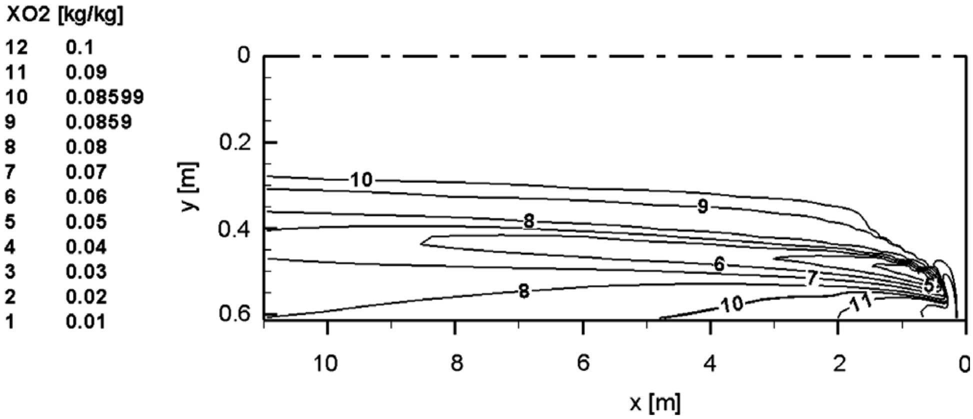

Fig. 3. Oxygen mass concentration in the horizontal plane through the plasma-jet inlet.

tures (in very narrow zone up to 3500 K), Fig. 2, originating from plasma-jet and intensive combustion in the region. Considerable mass flow rate of much colder air–coal dust mixture blows off the zone of plasma influence in downstream direction and 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 decreases 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, Fig. 1. 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.

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 consumption 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 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 Fig. 3, where there is a rapid combustion of carbon-monoxide and hydrogen, giving a very small concentration of combustible gases at the duct outlet Fig. 4. 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.

4.2. Thermal effect of the plasma torches

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

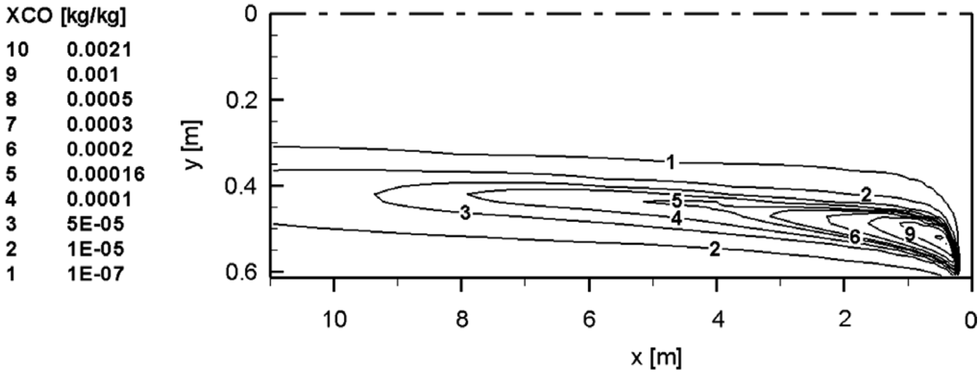

Fig. 4. Carbon-monoxide mass concentration in the horizontal plane through the plasma-jet inlet.

Table 1
Thermal effect of 200 kW plasma torches for different lengths of the case-study air–coal dust mixture duct

Duct length (m)	3.0	4.0	5.0	9.0	10.0
Energy output per time unit (MW)	1.671	1.686	1.697	1.721	1.725
Thermal effect of plasma torches (MW)	0.701	0.716	0.726	0.751	0.755

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 200 kW). Energy output of the duel 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 u difference between energy output and energy of air–coal dust mixture entering the duct. The influence of the duct length to the thermal effect of plasma torches in the test-case considered has been predicted and given in Table 1. The model predicts the energy output 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. Energy output is increased to the very end of the duct (i.e., to the inlet into the furnace), but it changes very slowly downstream. The differences between sections of the duct are decreased downstream, due to the influence of the air–coal dust mixture to the thermal situation. The difference in energy output between the sections at 5.0 m and 9,0 m is only 1.5%. These considerations can help in optimizing the air–coal dust mixture duct length, as well as in evaluation of plasma torches power required to replace heavy oil burners. Thus, the plasma-system thermal effect can be discussed 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-AI 210 $\mathrm{MW_e}$ 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 of 2.5 t/h 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 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].

5. Conclusions

Instead of usual system of heavy oil burners for pulverized coal ignition and combustion stabilization in utility boiler furnaces, plasma torches are built in air–coal dust mixture ducts and applied for the purpose, in order to achieve the savings of liquid fuel. The 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 rectangular air–coal dust mixture ducts with constant cross section area, having two opposite plasma torches, for 210 $\mathrm{MW_e}$ 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 regarding corresponding savings of liquid fuel.

In general, results of simulations strongly depend on operating conditions. 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, for different operation regimes.

Simulation of processes, based on the submodels verified with respect to the laboratory measurements, can be successfully applied in analysis 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 expenses and development period.

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