NUMERICAL ANALYSIS OF THE FLUE GAS-COAL PARTICLES MIXTURE FLOW IN BURNER'S DISTRIBUTION CHANNELS WITH REGULATION SHUTTERS AT THE TPP NIKOLA TESLA – A1 UTILITY BOILER

by

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Pulverized coal particles concentration distribution across the burner's distribution channels, especially where plasma torches are installed, is one of the key issues for efficient implementation of plasma system for liquid fuel free combustion support at the pulverized coal fired boilers. The possibility of pulverized coal particles concentration increase at the lower burner channels of TPP Nikola Tesla – A1 boiler using regulation shutters is analyzed experimentally and numerically. Subject of present work is two-phase flue gas-particles mixture flow in burner's distribution channels with regulation shutters installed at the TPP Nikola Tesla – A1 boiler. Aim of this work is to optimize position of implemented system of shutters to achieve desired concentration and velocity distribution in channels with plasma torches, using numerical modelling. Experimental investigation was performed for the verification of proposed mathematical model for the prediction of the analyzed two-phase flow. Based on verified model, numerical parametric analysis was done. Obtained results of gas phase velocity field, coal particles concentration field, velocity and concentration profiles clearly show the dependence between shutters position and the coal particles mass flow rate and concentration distribution at the outlet cross-section of the burner's distribution channels. According to the numerical optimization results suitable modification of the shutter system is proposed.

Key words: *numerical analysis, two-phase flow, flue gas-pulverized coal mixture, burner's distribution channels, utility boiler*

Introduction

Thermal power plants in Serbia fired by pulverized lignite are encountered with the problems related to combustion stability during the periods when low quality coal is fed into the boiler's furnace or in operation close to the technical minimum. Usually, heavy oil burners are used for the boiler start-up and fire support. Annual consumption of liquid fuel at the thermal

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power plants in Serbia is estimated at the level of 100 000 tones with more than a half of this amount used for the fire support. Increase of liquid fossil fuel share in energy balance of thermal power plants in Serbia, could be expected in the near future due to the lower coal quality tendency with expected increase of the ash content and even higher moisture content in the raw lignite supplied to the thermal power plants.

Due to the high market price of liquid fuels compared to the price of lignite it is of highest priority to decrease the liquid fossil fuel consumption in the utility boilers. In order to replace existing way of combustion support by liquid fuel, new concept based on plasma generators was introduced [1]. The possibilities of plasma technology for combustion support have been continually investigated for over the 30 years that involved wide spectrum of different coals and burner types [2]. The pioneer works in this field were started in USA, Canada, and Russia. Today, the problem of combustion support is not so actual in developed countries like USA, Japan, Germany *etc*. due to the use of highly reactive, enriched coals. The plasma system has been already applied at industrial boilers in Russia, Kazakhstan, Ukraine, Mongolia, China, Australia, Slovakia, Korea *etc*. and it is for the first time introduced in Serbia at the TPP Nikola Tesla unit A1, fired by pulverized coal, with low calorific value and high content of moisture, obtained from Kolubara mine, crushed inside the mill-ventilator where it was partially dried with flue gas recirculation on it's path to the furnace.

The plasma system is based on the idea to partially gasify pulverized lignite before it enters the furnace, making it more reactive and ready for instantaneous combustion, so there is no need to use liquid fuel for fire support. The air plasma with temperature of around 5000 K is blown into burner's channel with flue gas-coal particles mixture. The part of flue gas-coal particles mixture that passes through the high temperature zone of plasma becomes rapidly heated which results in crushing of coal particles into fragments, so the reaction surface of coal is significantly increased. Then devolatilisation and partial gasification of char (coke residue) takes place. In that way chain reaction is started and the rest of the flue gas-coal particles mixture undergoes thermo-chemical changes. This process is in some way similar to spark ignition in car engines.

Plasma has high energy concentration and great number of chemically active centers (atoms, ions, radicals, electrons *etc*.), which makes the process of plasma coal gasification and combustion much more efficient than classical methods. Thermo-chemical transformations of coal particles are 3-4 time faster due to the influence of plasma-chemical treatment. The concentration of active centers during the coal combustion in air plasma flame with temperature of 3000 K is around 7.5% and corresponding concentration in the flame with temperature of 1800 K is approximately 1%.

Different coals types require different operating conditions of plasma system in order to achieve desired level of gasification. Usually, ratio of plasma electric power to burner's heat power is in the range of 0.5-2%. This ratio is in the lower range for the coals with higher reactivity (higher content of volatiles), just like the Kolubara lignite. Still, disadvantage of using the Kolubara lignite is its high content of moisture (even more than 50 mass %) and ash (15 mass %) as well as relatively low temperature of ash melting. The product of plasma treatment of pulverized coal is the mixture of gaseous fuel (CO, H_2, C_nH_m) and reactive char (coke residue) with high specific surface on the temperature of ~900 °C. This solid-gaseous highly reactive fuel enters the furnace where it is mixed with secondary air and becomes fully burnt at the temperature of approximately 1200 °C.

Additional benefit from plasma coal gasification is that loses due to incomplete combustion in the furnace is expected to be decreased. Also, emission of NO_x can be up to 50% lower in the case when plasma system is in operation. This was confirmed both experimentally and numerically [3], where it is reported that NO_x emissions were reduced twice and amount of unburned carbon was reduced four times with the plasma combustion stabilization. Implementation of the plasma combustion support is not only economically justified due to reduction of liquid fuel use, but it has positive impact on the environment, too.

One of the key parameters of plasma technology for combustion support at the pulverized coal boilers is the reactant mass concentration, both pulverized coal particles and the oxygen, in the flue gas-coal particles mixture where plasma-chemical treatment has to take place. At the same time values of the gas phase velocity in the same area have to be as low as possible to prolong particle residence time in the high temperature plasma zone, and accordingly termo-chemical conversion of the solid fuel. Optimization of those complex technological parameters is of the great importance for efficient implementation of the plasma technology for liquid oil free combustion support at the pulverized coal boilers.

Numerical modelling of the two-phase flow in the real boiler's distribution channel geometry, as a tool for process parametric optimization, is widely accepted in the common industrial practice. Experimental investigation results are used as the input data and for mathematical model verification. Verified model is used for parametric analysis of the influence of angular position of regulation shutters on gas phase velocity field, solid phase concentration field and mass flow rate in the burner's distribution channels, for different pulverized coal mass flow rate and particle size distribution.

Burner's distribution channels geometry

TPP Nikola Tesla – A1 at Obrenovac, Serbia, with electrical power output of 210 MW, has a utility boiler with the following steam parameters: production 650 t/h, pressure 135 bar, and temperature 540 ºC. The utility boiler is equipped with the six burner's packages (consisting of eight vertically installed burner subchannels) for tangential combustion of pulverized lignite in the furnace. Plasma system for combustion support is installed on two of six burner's packages (marked with the numbers 12 and 15) at the lower four subchannels, at horizontal sections approximately 4 meters before the furnace entrance.

Burner's distribution channels are connected to the mill-ventilator, where up to 65 t/h of lignite with guaranteed lower calorific value of 6300-6700 kJ/kg is prepared for combustion (pulverized and dried to approximately 15 mass % moisture content). Drying and transporting agent is the mixture of flue gas recirculating from the top of the furnace and primary preheated air. After mills, the flue gas-coal particle mixture at the temperature in the range of 160-180 ºC passes through the upper burner's distribution subchannels with regulation shutter system, as shown in fig. 1.

The purpose of the regulation shutter system is to increase concentration of coal particles in the four lower burner channels with installed plasma torches. Totally, ten shutters in three groups are installed in attempt to provide sufficient gas and the solid phase distribution at eight burner's subchannels, as shown in fig. 2.

Shutters group (A), is positioned in subchannels 5-8, on the left side to upper burner channels. All shutters are jointly connected and regulation in these subchannels is achieved by rotating around their longitudinal axis. Second group of shutters (B), similarly connected to

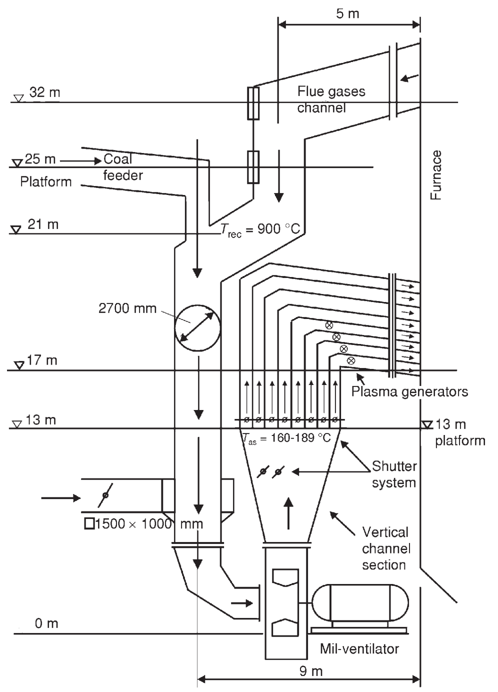

Figure 1. Schematics of the burner's distribution channel with the shutters

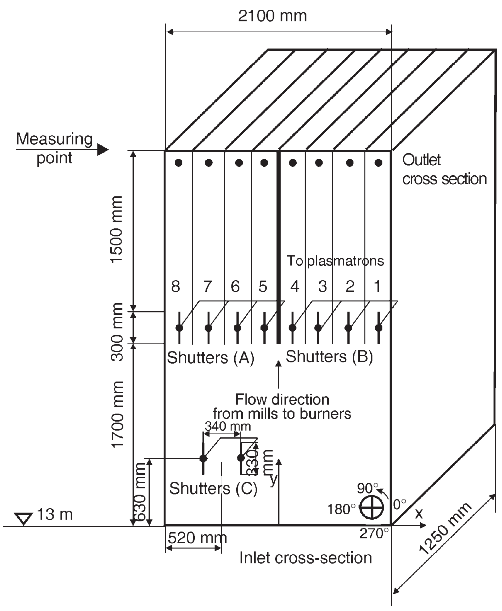

Figure 2. Geometry and dimensions of burner's distribution channels with shutters regulation system

move together, regulates flue gas-coal mixture flow in subchannels 1-4 on the right side, marked with „To plasmatrons“, (fig. 2). Counterclockwise international convention was used to express shutter group angular position. Shutter group (B) can be rotated continuously in the angle range of 0-90°, but shutter group (A) can be positioned only at discrete angular positions in angle range of 0-90° (90° – denotes opened subchannels, 60°, 30°, and 0° – denotes closed subchannels). Regulation shutters group (C) positioned just below group (A) can also be rotated continuously in the angle range of 0-90°. Shutters group (C), is designed to direct pulverized coal particles to the group of subchannels that transfer mixture to the plasma zone.

Experimental investigation of the two-phase flow in the burner's distribution channels

Moderate set of experimental measurements have been performed on the burner's distribution channels, in various boiler operation regimes at measuring points presented on fig. 2. Measurement procedures included: (1) velocity distribution measurement at the burner's distribution subchannels using Pitot probe, thermocouple, gas analysis, and (2) pulverized coal particles concentration measurement inside the subchannels using commercial "Acoma" device capable to isokinetically collect pulverized coal particles for determination of the concentrations in the subchannels. Measured results served as boundary conditions for the numerical simulations and for mathematical modeling verification.

Before measurements started, shutters have to be precisely positioned and their positions have to be registered. Velocity is measured for each of subchannels at eight measuring points along the channel depth. To achieve high accuracy of the measurements at each measuring point two measurement were performed. Sampling probe for concentration measurement has

Table 1. Regime 1, some of the boiler and mill-ventilator parameters

Furnace temperature	[°C]	870-900
Flue gases temperature	[°C]	840
Flue gas-coal particles mixture temperature	[°C]	168
Coal powder total mass flow, mill-ventilator 12	[kgs^{-1}]	7.687
Gas phase total mass flow, mill-ventilator 12	[kgs^{-1}] [Nm^3s^{-1}]	52.53 44.14
Inlet coal moisture	[mass%]	46.5
Pulverized coal moisture (at the measuring points)	[mass%]	13.5

been also positioned in eight sampling points for each subchannel. Collected pulverized coal particles from eight sampling points, sampled during equal time period, represent one sample. There were eight pulverized coal particles samples, one for each subchannel. Total sampling time in one subchannel was 4 minutes. After sampling, mass of every sample has been measured. According to the obtained values, coal particles flow in one subchannel and total mass of coal particles has been determined. Coal particle size distribution and moisture residue content of the representative pulverized coal particle samples have been analyzed too.

Table 2. Regime 1, gas phase, velocity and flow rate values

Subchannel number	8	7	6	5	4	3	2	1
x-coordinate [m]	–0.915	–0.655	–0.390	–0.130	0.130	0.390	0.655	0.915
v [ms^{-1}]	24.4	26.9	25.5	30.2	26.4	29.7	27.1	24.3
$\dot{V}$ [Nm^3s^{-1}]	4.95	5.43	5.17	6.23	5.46	6.08	5.65	5.17
$\dot{m}$ [kgs^{-1}]	5.89	6.46	6.15	7.41	6.50	7.24	6.73	6.15

Burner's distribution channels are connected at the mill-ventilator exit, where coal particle concentration is not constant across the channels width (along the x-axis). As measuring points are located only at outlet cross-section, it was necessary to provide initial measurements with all shutter groups in opened position =90° to determine the inlet coal concentration and gas phase velocity profiles, here denoted as Regime 1.

Some of the boiler and mill-ventilator parameters for Regime 1 are presented in tab. 1. Velocity and flow rate values for gas phase in subchannels are presented in tab. 2. Mass flow rate and concentration values for coal powder particles in subchannels, are presented in tab. 3.

Table 3. Regime 1, pulverized coal particles, solid phase, mass flow rate, and concentration values

Subchannel number	8	7	6	5	4	3	2	1
x-coordinate [m]	–0.915	–0.655	–0.390	–0.130	0.130	0.390	0.655	0.915
$\dot{m}$ [kgs^{-1}]	0.435	0.738	0.779	0.855	0.807	1.016	0.922	2.136
c [$kgNm^{-3}$]	0.09	0.14	0.15	0.14	0.15	0.17	0.16	0.41
C [kg coal/kg gas]	0.07	0.11	0.13	0.12	0.12	0.14	0.14	0.35

Table 4. Regime 2, main boiler and mill-ventilator parameters

Furnace temperature	[°C]	855-900
Flue gases temperature	[°C]	–
Flue gas-coal particles mixture temperature	[°C]	219
Coal powder total mass flow, mill-ventilator 12	[kgs^{-1}]	6.40
Gas phase total mass flow, mill-ventilator 12	[kgs^{-1}] [Nm^{3}s^{-1}]	55.3 46.94
Inlet coal moisture	[mass%]	51.80
Pulverized coal moisture (at the measuring points)	[mass%]	11.31

Velocity profile used as initial conditions for numerical calculations at inlet cross-section is presented in tab 4.

Velocity of the gas phase and pulverized coal concentration distribution in the subchannels are influenced by mill-ventilator working characteristics, as can be seen from tab. 2 and tab. 3. Gas phase velocity is evenly distributed across burner's distribution subchannels (within 10%) while pulverized coal particles distribution has increased amount in the subchannel number 1 (0.35 kg coal/kg gas), subchannels from 2-7 have almost equal particles concentration (0.11-0.14 kg coal/kg gas) and last subchannel number 8 has reduced concentration (0.07 kg/kg gas). Experimental measurements have clearly shown need of implementation of the suitable system capable to redistribute gas and solid phase flow across the subchannels in a way to decrease gas phase flow together with increasing of the particle concentrations at lower subchannels (1-4) and to increase gas phase flow rate and decrease particle concentrations at upper burner's subchannels (5-8).

Other experimental regimes have been used for mathematical model verification *i. e.* comparison of measured with numerical results. As representative operational regime is used Regime 2 with shutters (A) and (B) in opened position (90°) and shutters (C) at angular position of 60°. Relevant mill-ventilator parameters, gas phase velocity and flow rate values, pulverized coal particles mass flow rate, and concentration values are presented in tab. 4, 5, and 6.

Table 5. Regime 2, gas phase, velocity and flow rate values

Subchannel number	8	7	6	5	4	3	2	1
x-coordinate [m]	–0.915	–0.655	–0.390	–0.130	0.130	0.390	0.655	0.915
v [ms^{-1}]	29.1	31.5	33.2	34.1	34.2	33.6	32.2	30.0
$\dot{V}$ [Nm^{3}s^{-1}]	4.82	5.63	5.73	6.42	6.31	6.80	6.09	5.14
$\dot{m}$ [kgs^{-1}]	5.7	6.6	6.7	7.6	7.4	8.0	7.2	6.1

Mathematical modeling of the two-phase flow in burner's distribution channels

Gas phase was treated by Eulerian approach and its values and parameters were defined as function of spatial co-ordinates, while solid phase was treated by Lagrangian approach.

Continuity (1) and Navier–Stokes (2) equations describe the motion of the fluid (gas). Turbulence is modelled by the standard k-ε model (eq. 3, 4, and 5), [4-6].

Table 6. Regime 2, pulverized coal particles, mass flow rate and concentration values

Subchannel number	8	7	6	5	4	3	2	1
x-coordinate [m]	–0.915	–0.655	–0.390	–0.130	0.130	0.390	0.655	0.915
$\dot{m}$ [kgs^{-1}]	0.56	0.34	0.53	0.65	0.66	0.74	0.97	1.95
c [Nm^{3}s^{-1}]	0.099	0.070	0.092	0.102	0.105	0.108	0.160	0.379
C [kg coal/kg gas]	0.085	0.060	0.079	0.086	0.089	0.093	0.135	0.320

$$\frac{\partial(\rho U_i)}{\partial x_i} \quad 0 \tag{1}$$

$$\frac{\partial}{\partial x_j} \quad \rho U_i U_j \quad \overline{\rho u_i u_j} \quad \mu \frac{\partial U_i}{\partial x_j} \qquad \frac{\partial P}{\partial x_i} \quad S^P_{u_j} \tag{2}$$

$$\frac{\partial}{\partial x_j} \quad \rho U_j k \quad \frac{\mu_{\text{eff}}}{\sigma_{\text{k}}} \frac{\partial k}{\partial x_j} \qquad P_{\text{k}} \quad \rho\varepsilon \quad S^p_k \tag{3}$$

$$\frac{\partial}{\partial x_j} \quad \rho U_j \varepsilon \quad \frac{\mu_{\text{eff}}}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \qquad \frac{\varepsilon}{k}(C_{\varepsilon 1} P_{\text{k}} \quad C_{\varepsilon 2}\rho\varepsilon) \quad S^P_\varepsilon \tag{4}$$

$$\mu_{\text{eff}} \quad \mu \quad \mu_{\text{t}}, \quad \mu_{\text{t}} \quad \frac{C_\mu \rho k^2}{\varepsilon}, \quad P_{\text{k}} \quad \mu_{\text{eff}} \quad \frac{\partial U_i}{\partial x_j} \quad \frac{\partial U_j}{\partial x_i} \quad \frac{\partial U_i}{\partial x_j} \tag{5}$$

Source terms $S^p_{u_i}$, S^p_k and S^p_ε in the eq. (2-4), due to the presence of the particles, are given according to literature [4]:

$$S^p_{u_i} \quad \frac{\partial}{\partial x_j} \quad \mu_{\text{ef}} \frac{\partial U_j}{\partial x_i}, \quad S^p_k \quad \overline{S^p_{u_i} u_i} \quad {}_i \quad \overline{u_i S^p_{u_i}} \quad \overline{u_i S^p_{u_i}}, \quad S^p_\varepsilon \quad C_3 \frac{\varepsilon}{k} S^p_k \tag{6}$$

The coefficient values, for the standard k-ε model are: $C_\mu = 0.09$, $C_{\varepsilon 2} = 1.92$, $\sigma_{\text{k}} = 1.00$, $C_{\varepsilon 1} = 1.44$, $C_3 = 0.7$, and $\sigma_\varepsilon = 1.3$.

In order to solve the system of equations, control volume method was used. The basis of the FORTRAN programming code is CAST code for single phase flow that is based on SIMPLE algorithm. Mathematical model was modified in the Laboratory for Thermal Engineering and Energy of the Vinča Institute of Nuclear Sciences, by introducing the additional source terms (6), that includes the presence of the particles [7].

To describe particle motion in the fluid flow, all relevant forces have to be taken into account. The origin of the forces with continual effect is the presence and influence of the continual phase on the particles and the gravity [8-10]. The origin of the forces with impulse effect is the particle collision with the walls and obstacles and interparticle interactions. The intensity of the force that acts upon the particle depends on its shape. In most of the practical cases the shapes of the particles are irregular. In mathematical model and numerical calculations presented in this paper particles are presented as ideal spheres.

The dominant force influencing the particles is the drag force which, takes into account influence of the fluid (continual) phase, on particle motion. It is represented with the expression:

$$\vec{F}_D \quad C_D \frac{\pi D_p^2}{4} \frac{1}{2} (\vec{U} \quad \vec{V}_p) \left| \vec{U} \quad \vec{V}_p \right| \tag{7}$$

where particle properties are denoted with subscript p, D_p is the moderate sphere particle diameter, and $C_D(Re_p)$ – the drag coefficient, depends on the particle Reynolds number $Re_p = D_p \rho \; \vec{U} \quad \vec{V}_p \; /\mu$.

Particles rotate with high angular velocities, due to frequent interactions with the walls and obstacles. In viscous fluid that rotation induces lift force and torque that have to be taken into account when calculating particle motion. Sphere particle rotation was analyzed in viscous fluid for small Reynolds numbers, the following expressions for the lift force and torque were obtained:

$$\vec{F}_L \quad \pi \frac{D_p^3}{8} \rho \vec{\omega}_p \quad \vec{V}_p [1 \quad G(Re_p)] \tag{8}$$

$$\vec{T} \quad \pi \mu D_p^3 \vec{\omega}_p [1 \quad g(Re_p)] \tag{9}$$

where $G(Re_p)$ and $g(Re_p)$ are the functions of particle Reynolds number and can be neglected.

In case of turbulent flow, rotation of fluid has to be taken into account by introducing the term (1/2) $\quad \vec{U}$ in the expressions (8 and 9):

$$\vec{F}_L \quad \pi \frac{D_p^3}{8} \rho \quad \vec{\omega}_p \quad \frac{1}{2} \quad \vec{U} \quad (\vec{V}_p \quad \vec{U}) \tag{10}$$

$$\vec{T} \quad \pi \mu D_p^3 \quad \vec{\omega}_p \quad \frac{1}{2} \quad \vec{U} \tag{11}$$

When the velocity gradient is present in the fluid through which the particle moves, the pressure field is no longer symmetrical, and the new force has to be introduced – Saffman force [10] for particle motion through very viscous fluid and for the velocity gradient perpendicular to direction to the particle motion. The intensity of the force is very important in the case of very small particles in near wall regions with high velocity gradients. For other cases intensity of Saffman force is relatively small. General expression for the Saffman force is given at [7]:

$$\vec{F}_S \quad 1.54 m_p \frac{\sqrt{\rho \mu}}{\rho_p D_p \sqrt{\left| \quad \left| \vec{V}_p \quad \vec{U} \right| \right|}} \quad (\vec{V}_p \quad \vec{U})^2 \tag{12}$$

The forces that should also be mentioned are of impulse nature and are induced by frequent collisions of particles with walls and obstacles and particle-particle collisions. In the case of particle-wall collision the model of particle hitting smooth surface was used. For mutual particle collisions, the most important is the frequency of collisions. Particle-particle collisions should be taken into account only in the case of high particle/fluid volume ratio. For the problem, presented in the paper, the particle/fluid volume ratio is low enough, so the modelling of particle-particle collision is not incorporated in the present model.

Particle motion was described by Newton's second law:

$$m_p \frac{d\vec{V}_p}{dt} \quad \sum_i \vec{F}_i \qquad I_p \frac{d\vec{\omega}_p}{dt} \quad \sum_i \vec{T}_i \tag{13}$$

For solving the equations of particle motion, semi-analytical approach was used. The time interval, during which the particle was tracked, was divided in subintervals. At the end of each of subintervals, particle position, velocity, and angular velocity were calculated. It was assumed that during each of subintervals the lift and Saffman forces are constant. In order to make this assumption valid, every subinterval has to be short enough. Differential equations of particle motion are:

$$\frac{\mathrm{d}\vec{V}_\mathrm{p}}{\mathrm{d}t} = \frac{1}{\tau_\mathrm{p}}(\vec{U} - \vec{V}_\mathrm{p}) + \vec{g}\left(1 - \frac{\rho}{\rho_\mathrm{p}}\right) + \frac{\vec{F}_\mathrm{L} + \vec{F}_\mathrm{S}}{m_\mathrm{p}} \tag{14}$$

$$I_\mathrm{p}\frac{\mathrm{d}\vec{\omega}_\mathrm{p}}{\mathrm{d}t} = \vec{T} \tag{15}$$

where τ_p is the particle response time. Particle response time can be assumed constant for a certain time interval, in which the analytical solution of the equations was searched. It is defined with expression:

$$\tau_\mathrm{p} = \frac{8m_\mathrm{p}}{\pi D_\mathrm{p}\mu C_\mathrm{D}\,\mathrm{Re}_\mathrm{p}} \tag{16}$$

Physically it represents capability of particle to adjust to local fluid velocity. For higher τ_p values, particle inertia is higher, and the change of its velocity is slower.

Presented flue gas-pulverized coal particles two-phase flow problem, was treated as two-dimensional, due to several reasons:

– longitudinal vertical cross-section of the channel in x-y plane (domain) is equally distant from the side-walls,
– the width of the domain, in z-axis direction, is relatively large (1.25 m), the influence of side-walls can be omitted, and flow symmetry is not disrupted,
– there are no curves or elbows, that can disturb flow parameters in z-direction in the considered part of the channel, and
– disturbances are induced by regulation shutters, in x-y plane only.

Two-dimensional numerical mesh of the longitudinal vertical cross-section of the channel was used. The domain was divided into 210 × 144 = 30240 identical rectangular cells. Length of each cell in vertical direction is 35 mm, and in horizontal direction 10 mm [11]. For numerical calculations only, the length of the channel was extended from 3.5 m (real length) to 5.04 m in order to attain uniform velocity profiles of gas phase and concentration profiles of coal powder particles, at sufficient distance from outlet cross-section, to reduce the influence of subchannel walls and especially to determine numerical calculations convergence problems.

Numerical simulation of two-phase flow in burner's distribution channel

Complete set of regimes that is relevant for numerical analysis and optimization of the shutter angular position is presented in tab. 7. Regimes 1-9 have constant mass flow rates of both phases but different angular position of shutter groups (B) and (C). Analysis of those numerical regimes can provide information about shutter group (B) and (C) influence on the system effectiveness. Mass flow rate of dried pulverized coal particles for regimes 1-9 and 13-18 was kept at 7.687 kg/s while for regimes 10-12, mass flow was maintained at minimum mill-ventilator capacity 4.33 kg/s. Influence of different total mass flow rate on its spatial distribution across the subchannels was analyzed by comparison of numerical results for a pair of regimes: regime 4 and 10 for (C) = 90°, regime 5 and 11 for (C) = 60°, and regime 6 and 12, for (C) = 30°. In regard to coal particle size distribution, measured representative pulverized coal particles size fractions were considered in numerical calculations for regimes 1-12, while in numerical regimes 13-18 only one of these fractions was considered. Effectiveness of the shutter system on solid phase distribution across the subchannels for 6 different pulverized coal fractions was numerically analyzed in regimes 13-18.

Table 7. Regimes analyzed in numerical calculations

Regime	(A) [°]	(B) [°]	(C) [°]	Gas phase mass flow rate [kg/s^{-1}]	Pulverized coal particles mass flow rate [kg/s^{-1}]	Coal particle size distribution
1	90	90	90			
2	90	90	60	52.53	7.687	
3	90	90	30			
4	90	60	90			
5	90	60	60	52.53	7.687	
6	90	60	30			30-60 m, 25% 60-90 m, 15% 90-200 m, 32% 200-500 m, 18% 500-1000 m, 6% >1000 m, 5%
7	90	45	90			
8	90	45	60	52.53	7.687	
9	90	45	30			
10	90	60	90			
11	90	60	60	52.53	4.33	
12	90	60	30			
13						30-60 m
14						60-90 m
15	90	60	30	48.98	7.687	90-200 m
16						200-500 m
17						500-1000 m
18						>1000 m

Mathematical model verification

Mathematical model verification has been performed by comparing the results of numerical calculations with data measured in experimental Regime 2. Figure 3 presents comparison of pulverized coal particles mass flow rate values in subchannels, obtained by experimental measurements and numerical simulation. As seen, mathematical model can be considered as good representation of investigated engineering problem, since results of subchannel mass flow rate values deviate from measured ones less than a 10%. Difference between numerically calculated and experimental for summary mass flow rates in left (subchannels 5-8)/ /right (subchannels 1-4) side of the channel is also below 10%, fig. 4.

Comparisons of gas phase mass flow rate values in subchannels and in left/right part of the channel, obtained by measurements and numerical calculations are presented in figs. 5 and 6. Difference between measured and calculated values of gas phase mass flow rates can also be considered satisfactory, since its values in subchannels are less than 9%, and ~2% for mass flow rates on left/right part of the burner's distribution channels.

Determination of the shutter group (C) influence

Influence of shutters group (C) to the velocity field can be observed from gas phase velocity profiles, at outlet cros-section, for three different shutter (C) angular positions (90º, 60º, and 30º) and shutters (A) and (B) in fixed positions, regimes 7, 8, and 9, presented in figs. 7 and 8 and tab. 7. With shutter group (B) in optimal position (angular position of 45º), velocity in the right subchannels (1-4) is significantly reduced and remains in range of 14-22 m/s. Further rotation of shutter group (B) <45° leads

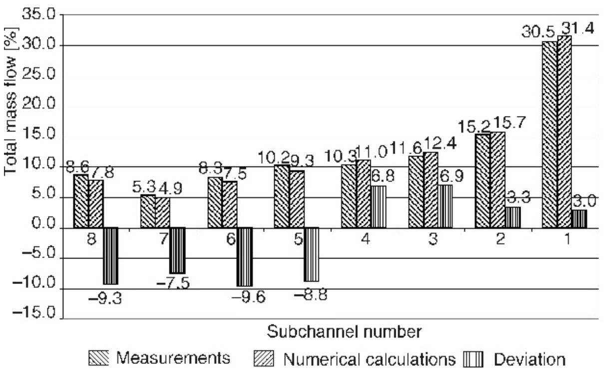

Figure 3. Measured and numerical values of pulverized coal particles mass flow rate in subchannels

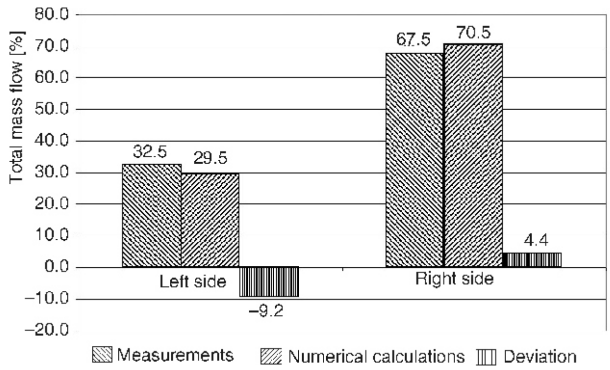

Figure 4. Measured and numerical values of pulverized coal particles mass flow rate in left/right part of the burner's distribution channels

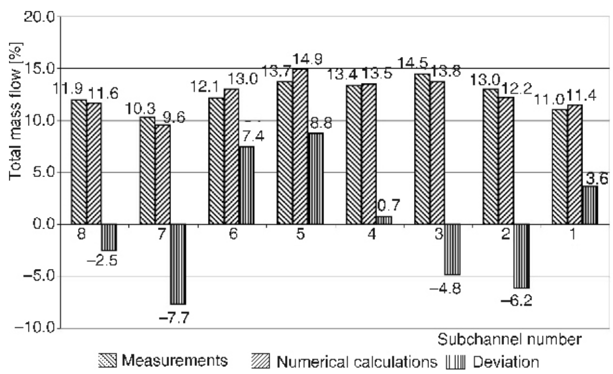

Figure 5. Measured and numerical values of mass flow rate for gas phase in subchannels

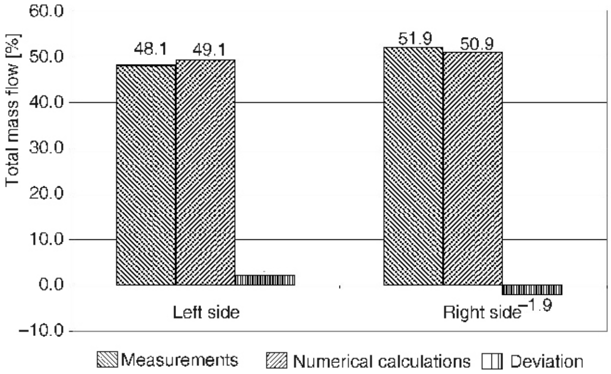

Figure 6. Measured and numerical values of mass flow rate for gas phase in left/right part of the channel

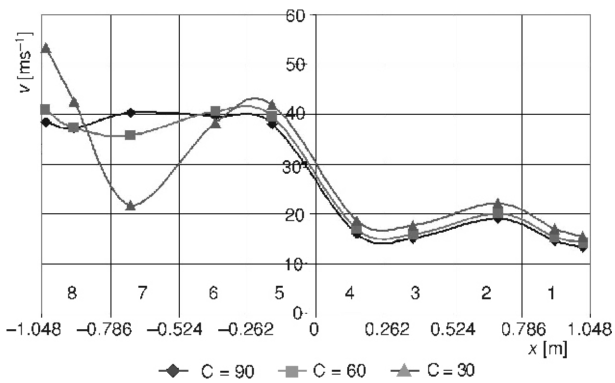

Figure 7. Velocity profiles, gas phase, outlet cross-section, (C) = 90°, 60°, and 30°, (A) = 90°, (B) = 45°

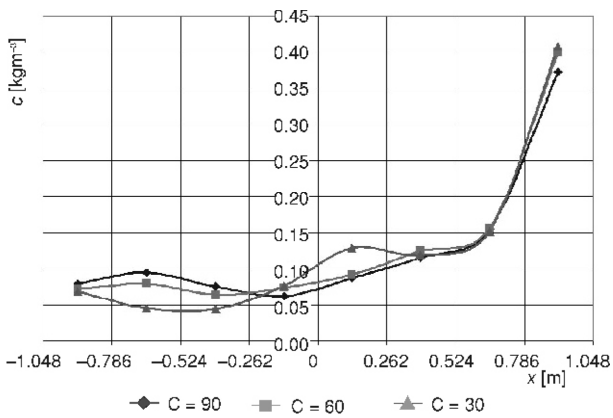

Figure 8. Concentration profiles, solid phase, outlet cross-section, (C) = 90°, 60°, and 30°, (A) = 90°, (B) = 45°

to critically small velocities in the subchannels on the right side causing deposition of the coal particles in the burners. Shutter's group (C) rotations from 30-90º does not influence any significant change in the velocity field on the right side of burner's distribution channels due to damping effect of shutters group (B). At higher angular positions, presented with a case (C) = 30º in fig. 7, on the left side of the channels (subchannels 5-8) there can be found more severe influence because shutters are obstacles for mixture flow causing velocity profile to become deformed in this area.

Figure 8 presents pulverized coal particles concentration profiles, at burner's distribution channels outlet cross-section, for three different discrete shutter group (C) positions 90º, 60º, and 30º, (regimes 7, 8, and 9), tab. 7. Concentration profile is mainly induced by mill-ventilator working characteristics with a majority of the particles concentrated in the first subchannels on the right side of the burner's distribution channels. From this point of view, it is evident that this shutter group does not significantly increase the particle concentration in the right subchannels (1-4). Concentration profile is almost unchanged in the first three subchannels, mainly influenced by initial distribution of the concentrations at the outlet from the mill, and partly, by angular position of the shutters group (B) fixed at 45°. In the subchannels on the left side, when shutters (C) = 30° pulverized coal particle concentrations are on the lowest level. Shutters belonging to the group (C) represent obstacle for two-phase flow in this part of the channel. Velocity of the gas phase in the subchannel number 8 is increased, due to free fluid flow between shutters and the channel wall, with minor coal particle mass flow, causing low concentration level.

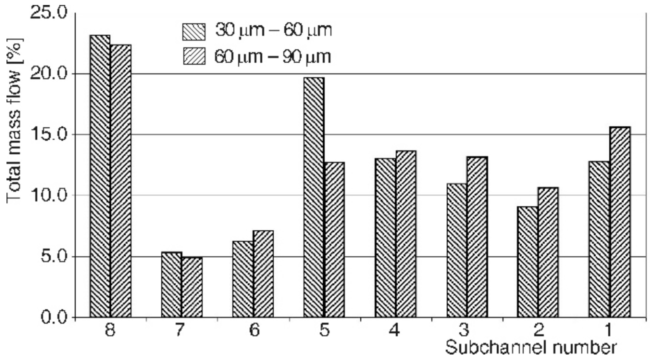

Figure 9. Mass flow distribution of the coal powder fractions 30-60 μm and 60-90 μm

Influence of pulverized coal mass flow rate

Influence of pulverized coal particles mass flow rate on its distribution was analyzed comparing numerical data of three regimes (with three different angular positions of shutters (C) – regimes 10, 11, and 12) with minimum pulverized coal mass flow rate (4.33 kg/s), and other three regimes (with same angular positions of shutters (C) – regimes 4, 5, and 6) with pulverized coal mass flow rate (7.687 kg/s). Mass flow distributions for the regimes were compared for a pair of regimes with the same shutter group position and different solid phase capacity (4-10, 5-11, and 6-12).

Obtained numerical results have shown that mass flow distribution of pulverized coal particles in the subsections of burner's distribution channels is independent of total coal mass flow rate, so shutters system remains effective with a change of mill capacity.

Effectiveness of shutters system for different coal particle fractions

Six regimes 13-18, tab. 7, each with only one narrow coal particle size fraction were considered in the analysis in a case of typical shutters position. The shutter group (B) with its position (60º), partially closes channel sections on the right side, reducing flow and inducing more uniform flow distribution of both phases in these sections. The shutter group (C), with angular position of 30º directs coal powder particles to the right side of the channel. Total mass flow of each narrow coal particle size fraction was the same for all regimes and equal to 7.687 kg/s. For this type of analysis inlet velocity profile was considered uniform (25 m/s), and distribution of the particle fractions at the inlet cross-section was also uniform.

Smallest particles (30-60 μm and 60-90 μm) have minimum inertia, and can easily drift with gas flow, so their distribution follow gas phase outlet profile, fig. 9. Largest particles (500-1000 μm and >1000 μm) with maximum mass and inertia, are much more influenced by interaction with shutters group (C) than by the gas phase flow, fig. 10. Majority of these particles fractions, are di-

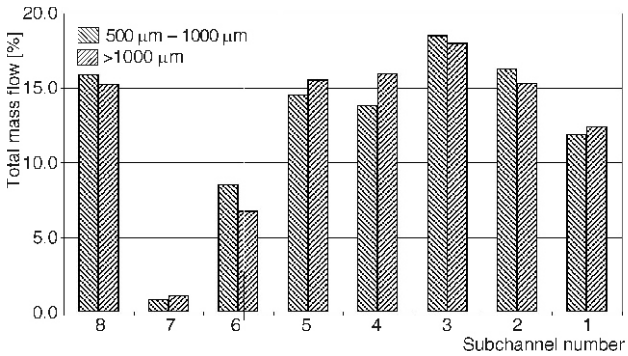

Figure 10. Mass flow distribution of the coal powder fractions 500-1000 μm and >1000 μm

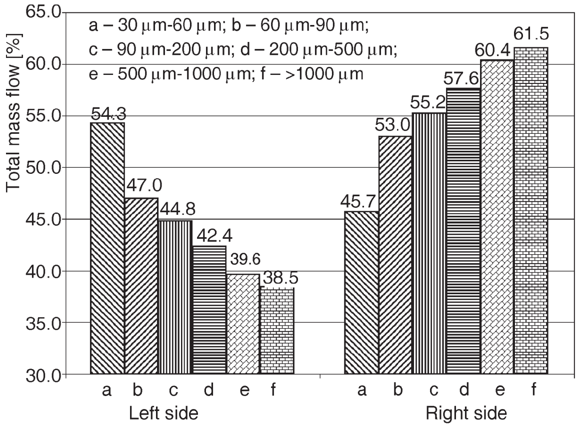

Figure 11. Mass flow distribution of various coal powder fractions on left/right side of burner's distribution channels

rected to the right side of the channel (60.4% of particles fraction 500-1000 μm and 61.5% of particles >1000 μm) due to the position of the shutters group (C) = 30º. Two-phase flow of both particle fractions is influenced by the shutters in a group (C) that are obstacles to the flow and prevent particles to reach the subchannels 6 and 7.

Mass flow distribution of six pulverized coal fractions, on the left/right part of the channel, is presented in fig. 11. It is important to point out that velocity field of gas phase has a major influence on distribution of smallest particles, and minimum influence on the largest ones, while shutters mainly influence behavior of larger particles. Effectiveness of the analyzed shutter system on the solid phase distribution across the subchannels is the highest for the biggest coal particles (fraction >1000 μm). As the size (mass) of the coal particles is decreasing the effectiveness of the analyzed shutter system for separation solid phase to the right side subchannels (to plasmatrons) is decreasing and for smallest fraction (30-60 μm) has opposite effect due to increased gas phase flow rate in the left compared to the right side subchannels.

Conclusions

Pulverized coal particles concentration over 0.3 kg coal/kg gas in all burner's distribution channels with plasma torches is one of the key parameter in efficient implementation of plasma system for liquid fuel free combustion support. Presented experimental measurements and numerical analysis of flue gas-pulverized coal particles two-phase flow in the burner's distribution channel of the utility boiler TPP Nikola Tesla – A1 with presented shutter system have shown:

- two-phase flow characteristics at the exit of the mill is strongly influenced by mill-ventilator operation that usually result in a non-uniform gas phase velocity and solid phase concentration distribution at the inlet cross-section of the burner's distribution channels,
- to resolve this problem of desired velocity and concentrations achievement of the two-phase flow in the coal mills exit chamber numerical modeling should be also used,
- shutter group (C) has strong positive influence on two-phase flow but still it could be improved by suitable reconstruction of this shutter system segment,
- by optimal angular position of shutter group (B) desired velocity range of 14-22 m/s in the subchannels with plasma torches could be achieved,
- effectiveness of the analyzed shutter system is not depending on coal mass flow rate,
- shutter system for pulverized coal redistribution across the burner's distribution subchannels has major influence on bigger coal particles with higher mass while smaller particles are easily drifted by gas phase flow,
- for a given burner's distribution channel and shutter system geom-

etry it has been shown that even optimal shutter position do not provide necessary pulverized coal particles concentration at all subchannels where plasma torches are installed, and

– in order to achieve demanding pulverized coal concentrations at burner's subchannels with installed plasma torches (where concentrations >0.3 kg coal/kg gas are needed), it is proposed system consisting the group of louvers with several constructive parameters: length and the angle of the louvers, spacing between the louvers, angle of the stationary louver positioning in the flow ducts, as well as the angle deflection of movable louvers.

Some measures are already taken at the TPP Nikola Tesla – A1 and newly developed system of louvers for more efficient redistribution of the pulverized coal particles is in the investigation phase.

Nomenclature

C – concentration, [kgkg^{-1}]
c – concentration, [kgNm^{-3}]
$\bar{c}$ – normalized concentration, [–]
$\vec{F}_D$ – drag force, [N]
$\vec{F}_L$ – lift force, [N]
$\vec{F}_S$ – Saffman force, [N]
g – gravity acceleration, [ms^{-2}]
I_p – moment of inertia for particle, [kgm^{-2}]
m_p – particle mass, [kg]
$\dot{m}$ – mass flow rate, [kgs^{-1}]
S_{ui}^p – source term for momentum, [kgm^{-2}s^{-2}]
S_k^p – source term for turbulent kinetic energy, [Jm^{-3}s^{-1}]
S_ε^p – source term for turbulent kinetic energy dissipation, [Jm^{-3}s^{-1}]
$\vec{T}$ – torque, [Nm]
u_i, u_j – velocity components, gas phase, time dependent, [ms^{-1}]
$\dot{V}$ – flow rate [Nm^{-3}s^{-1}] (at NTP conditions T = 0 °C and absolute pressure of 101.325 kPa)
$\vec{V}_p$ – particle velocity, [ms^{-1}]
v – velocity, [ms^{-1}]
$\bar{v}$ – velocity, non-dimensional, [–]
Re – Reynolds number, [–]

Greek symbols

$\vec{\omega}$ – angular velocity, [rad·s^{-1}]

Subscripts

D – drag
eff – effective
L – lift
p – particle
t – turbulent

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