Invited paper

MODELING OF PULVERIZED COAL COMBUSTION FOR IN-FURNACE NO_X REDUCTION AND FLAME CONTROL

by

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A cost-effective reduction of NO_x emission from utility boilers firing pulverized coal can be achieved by means of combustion modifications in the furnace. It is also essential to provide the pulverized coal diffusion flame control. Mathematical modeling is regularly used for analysis and optimization of complex turbulent reactive flows and mutually dependent processes in coal combustion furnaces. In the numerical study, predictions were performed by an in-house developed comprehensive three-dimensional differential model of flow, combustion and heat/mass transfer with submodel of the fuel- and thermal-NO formation/destruction reactions. Influence of various operating conditions in the case-study utility boiler tangentially fired furnace, such as distribution of both the fuel and the combustion air over the burners and tiers, fuel-bound nitrogen content and grinding fineness of coal were investigated individually and in combination. Mechanisms of NO formation and depletion were found to be strongly affected by flow, temperature and gas mixture components concentration fields. Proper modifications of combustion process can provide more than 30% of the NO_x emission abatement, approaching the corresponding emission limits, with simultaneous control of the flame geometry and position within the furnace. This kind of complex numerical experiments provides conditions for improvements of the power plant furnaces exploitation, with respect to high efficiency, operation flexibility and low emission.

Key words: *modeling, turbulent two-phase reactive flow, tangential firing of pulverized coal, combustion modifications, NO_x and flame control*

Introduction

Coal-fired energy conversion systems should provide both efficient and environmental friendly fuel utilization over a wide range of operating conditions, in order to meet ever increasing demands for energy and fuel savings but also severe emission limits. Clean and efficient combustion is crucial in extending operational life of power plant facilities as well. As precursors of photochemical smog oxides of nitrogen are considered to be among the most harmful pollutants emitted from utility boilers combusting pulverized coal. Combustion modification in the furnace is a cost-effective measure for reduction of NO_x

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emission from pulverized coal-fired utility boilers. In the same time, providing the pulverized coal diffusion flame control within the furnace is essential for stable and safe operation of the boiler facility. These improvements are based on optimization of complex mutually dependent processes in furnaces during exploitation. In order to analyze turbulent two-phase reactive flows in coal combustion furnaces mathematical modeling is used worldwide [1-23].

Research efforts continuously focus on modeling NO_x formation/destruction reactions in pulverized coal combustion [1-17]. Nitric oxide (NO) is the most abundant NO_x from coal combustion. The simulations often neglect prompt NO (significant only in strongly fuel-rich flames), while considering fuel NO, typically accounting for 75-95% of the total NO in coal combustors [15, 17] and thermal NO, becoming important for the flame temperatures above 1600-1800 K [15]. As opposed to post-combustion clean-up, in-furnace combustion modifications (primary measures) offer a cost effective and relatively simple method of NO_x control [15]. Different NO_x removal techniques of this kind are numerically analyzed and optimized [1-14], often in tangentially fired furnaces (TFF) [1-11]. Flow pattern and inlet air velocities effect on NO_x emission from TFF was studied in [10]. Efficient and cost-effective method for reducing NO_x emission is flue gas recirculation [3, 14]. Fuel and air staging are a group of methods extensively used in a number of combinations. Parameters of overfire air (OFA) systems (like OFA port position and the overfire air ratio) were examined in a variety of configurations [2, 4, 7-12]. Multi-group of separated over fire air (SOFA) nozzle arrangement is tested in [8]. Different OFA offsets (positive and counter) relative to the direction of the secondary air jet were also considered [9]. TFF combustion system combining horizontal bias burner (fuel rich/lean burner) with SOFA [1] and deep air staging by using large amount of additional air through special ports above the burners and OFA ports [6] proved to be promising approaches. Individual or combined effects of pulverized coal and preheated air distribution over individual burners and burner tiers, grinding fineness and quality of coal and air ingress were examined in [7]. When applying the furnace sorbent injection desulfurization method influence of the sorbent transport air on NO_x emission was also studied [3]. A new stereo-staged combustion technique combines horizontal bias combustion burners and offset secondary air (horizontal fuel and air staging) with pulverized coal reburning and SOFA (vertically fuel and air staging) [5]. Moderate and intensive low oxygen dilution combustion is another novel approach to reducing NO_x emission in which chemical reactions take place in almost the entire volume of combustion chamber so that the influence of turbulence-chemistry interactions on combustion is crucial [13]. In all of these methods based on combustion tunings flow field and turbulent mixing between streams play an essential role.

Since these measures completely change the flow and temperature situation in the combustion chamber they also strongly affect the pulverized coal diffusion flame position, both vertical and lateral, and thus the flame has to be also carefully controlled, not to disturb the safe operation of the furnace and boiler. The flame geometry basically depends on firing configuration; in turn, it will influence the heat and mass transfer processes in furnaces and the conditions for formation and depletion of nitrogen oxides. Consequently, coal combustion, flame characteristics and NO_x content must not in any way be treated separately. A proper and in-depth understanding of turbulent multiphase reactive flow is vital for this kind of analysis and it can be achieved efficiently by mathematical modeling, especially in conjunction with measurements. Furnaces with tangential firing, like in this work, were extensively studied numerically, either in conjunction with NO_x emission [1-11], or pointing out the importance of velocity field and flame configuration for this type of coal firing [18-20, 22, 23] and predicting the influence of pulverized coal and combustion air distribution over the burners and tiers on the flame characteristics [21].

The NO_x emissions from power plants utilizing Serbian lignites are not extremely high but still considerably exceed new European emission limits. In this paper, combustion modifications in 350 MW_e Kostolac-B utility boiler TFF were investigated, affecting both the NO_x emission and the pulverized coal flame. An in-house developed 3-D differential mathematical model of furnace processes, including the fuel- and thermal-NO formation/destruction reactions, validated against available measurements in the case-study boiler units [7, 21-23], was used for the analysis. The comprehensive combustion code offers a balance between sophistication of submodels describing individual processes and computational practicality. The NO formation and depletion mechanisms were studied in dependence on two-phase gas-particle reactive turbulent flow and pulverized coal diffusion flame, accounting for extremely complex interactions between influencing parameters. Impact of various operating conditions in the case-study furnace, like the fuel and the combustion air distribution over the burners and tiers, fuel-bound nitrogen content and grinding fineness of coal, on the NO_x emission and flame, were investigated individually and in combination. Complex numerical experiments of this kind can help to optimize flow, combustion and heat transfer and improve the furnace exploitation regarding emission and efficiency.

Mathematical model, numerical code and software tool

Detailed description of the three-dimensional comprehensive differential mathematical model of gas-particle two-phase turbulent reactive flow in pulverized coal-fired utility boiler furnace at stationary conditions can be found in [7, 21-23]. Eulerian-Lagrangian approach to the two-phase flow [24] is applied. Gas phase is described by time-averaged Eulerian conservation equations for mass, momentum, energy, gas mixture components concentrations, turbulence kinetic energy and its rate of dissipation. In general-index notation:

$$\frac{\partial}{\partial x_j}\left(\rho U_j \Phi\right) = \frac{\partial}{\partial x_j}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial x_j}\right) + S_\Phi + S_\mathrm{p}^\Phi \tag{1}$$

where S_p^Φ, ρ, U_j, Γ_Φ, S_Φ are additional sources due to particles, gasphase density [kgm^{-3}], velocity components [ms^{-1}], transport coefficient and the source term for general variable Φ, respectively. The k-ε turbulence model is used to close the equations (1). Dispersed phase is described by differential equations of motion, energy and mass change in Lagrangian field and the particle velocity vector is a sum of convective and diffusion velocity. Diffusion model of particles dispersion by turbulence is used instead of stochastic approach which requires more trajectories for stable and reliable numerical solutions. Impact of particles on gas phase is accounted for by PSI Cell method, while collisions between particles are neglected (two-way coupling). Turbulence modulation by dispersed phase [25, 26] is also taken into account in contrast to many other predictions performed by comprehensive combustion codes. This phenomenon is far from being fully resolved. Attenuation or augmentation of turbulence depends on different characteristic length- or time-scales of dispersed phase and turbulence, like particle diameter to turbulence length scale ratio and ratio between particle response time and Kolmogorov time scale. This influence was examined for pulverized coal particles with initial mean diameter of 150 μm, numerically tracked in turbulent reacting particle-laden flow. On average, the particles caused about 28% of turbulence kinetic energy decrease [22]. Continuity equation for particle number density is given in the form of equation (1). A convection-

-radiation heat transfer is considered and radiative heat exchange is modeled by the six-flux method which solves total radiation fluxes, used to find the radiative energy source term in the gas-phase enthalpy equation and the radiative heat transfer rate to a single particle. Flue gas and wall total emissivities are assigned values of $\varepsilon_g = 0.35$ and $\varepsilon_w = 0.85$ [27]. Calculation procedure for prediction of the furnace walls ash deposits impact on the radiative heat exchange was also developed [28] and used within the code. There is conduction and radiation through the deposits layer and physical properties influencing the heat transfer are effective thermal conductivity and emissivity of the layer fire side surface. Available experimental data on combustion considered the coal particle kinetics for Serbian lignites with respect to the entire particle, which determined the modeling approach. Individual processes in complex process of pulverized coal combustion were treated on the basis of global particle kinetics, obtained experimentally. Coal particle combustion is modeled within the "shrinking core" concept and with respect to the char combustion, which is by far slower process compared to devolatilization and the volatiles oxidation. The coal particle mass change, equal to the reaction rate, is given in combined kinetic-diffusion regime [7, 21, 22]. Mass and heat addition due to combustion is considered in equations (1) by the sources due to particles. Kinetic parameters of the case-study coal, *i. e.* lignite Drmno, were determined in vertical cylindrical laboratory furnace [21, 22]. This approach may be adjusted easily to include additional heterogeneous and homogeneous reactions [29]. Initial and boundary conditions usual for elliptical partial differential equations are applied and the conditions near the walls are described by the standard "wall functions".

The NO_x formation and destruction reactions submodel was incorporated into the complex combustion code. It is executed after the flame structure was predicted, in a "post-processor" way [15], because the pollutant species does not affect the flame structure significantly. Simplified chemical models in conjunction with detailed CFD calculations were used for the reasons of practicality and computational efficiency. The thermal NO formation/destruction reactions can be predicted by Zeldovich expression with respect to a single reaction rate constant [15]. The NO_x submodel comprises also the fuel NO formation/depletion reactions [30-32] through hydrogen cyanide (HCN) as an intermediate compound from volatilization. In the selected approach HCN is formed by direct transformation of coal-bound nitrogen during devolatilization, while NH_3 is produced by secondary reactions [33]. Nitrogen released within NH_3 is taken into account through equivalent nitrogen content. The chosen NO formation model is related to De Soete global-reaction kinetics [31, 32]. Fuel NO formation reaction rate is given as:

$$\frac{\mathrm{d}\chi_{\mathrm{NO}}}{\mathrm{d}t} = A_1 10^{10} \chi_{\mathrm{HCN}} \chi_{\mathrm{O_2}}^{\alpha} \exp\left(\frac{-33732.5}{T}\right) \tag{2}$$

$$\begin{aligned} \chi_{\mathrm{O_2}} &\le 4.10\cdot 10^{-3}, & \alpha &= 1 \\ 4.10\cdot 10^{-3} < \chi_{\mathrm{O_2}} &\le 1.11\cdot 10^{-2}, & \alpha &= -3.95 - 0.9\ln\chi_{\mathrm{O_2}} \\ 1.11\cdot 10^{-2} < \chi_{\mathrm{O_2}} &\le 0.03, & \alpha &= -0.35 - 0.1\ln\chi_{\mathrm{O_2}} \\ \chi_{\mathrm{O_2}} &> 0.03, & \alpha &= 0 \end{aligned} \tag{3}$$

Coefficient $0 < \alpha < 1$ depends on the local concentration of oxygen [31]. As proposed by Lockwood and Romo-Millares [16] for fuel-lean conditions that prevail in pulverized coal-fired furnaces, pre-exponential factor A_1 is increased by 3.5 compared with original value $A_1 = 1$ (De Soete [31], more proper for fuel-rich conditions). The best fit, based on experimental NO emission values, was found to be $3.5 \cdot 10^{10}$ s^{-1} [16] and was extensively used for NO_x predictions in utility scale boilers. In this work, calculations were performed with different values of pre-exponential factor A_1 depending on local conditions. For NO depletion rate the expression has been selected according to the literature [30], as a function of mole fractions: $\chi_{\mathrm{HCN}}, \chi_{\mathrm{O_2}}, \chi_{\mathrm{NO}}$, as follows:

$$\frac{\mathrm{d}\chi_{\mathrm{NO}}}{\mathrm{d}t} = -3 \cdot 10^{12} \chi_{\mathrm{HCN}} \chi_{\mathrm{NO}} \exp\left(\frac{-30208.2}{T}\right) \tag{4}$$

Partial differential equations for HCN and NO are solved in Eulerian field, equations (5). The source of HCN, S_{HCN}, comprises both the HCN release by devolatilization and HCN depletion in the gaseous phase, while the source of NO, S_{NO}, is obtained in dependence on the total net formation/destruction rate of NO. Mass fractions of HCN and NO are given by X_{HCN} [$\mathrm{kgkg^{-1}}$] and X_{NO} [$\mathrm{kgkg^{-1}}$], respectively, while Γ_{HCN} and Γ_{NO} are corresponding transport coefficients. The NO_x submodel is described in details and validated by comparisons with available emission measurements on the case-study boiler units [7]:

$$\begin{aligned} \frac{\partial}{\partial x_j}\left(\rho U_j X_{HCN}\right) &= \frac{\partial}{\partial x_j}\left(\Gamma_{HCN} \frac{\partial X_{HCN}}{\partial x_j}\right) + S_{HCN} \\ \frac{\partial}{\partial x_j}\left(\rho U_j X_{NO}\right) &= \frac{\partial}{\partial x_j}\left(\Gamma_{NO} \frac{\partial X_{NO}}{\partial x_j}\right) + S_{NO} \end{aligned} \tag{5}$$

Discretization of partial differential transport equations is performed by control volume method and hybrid-differencing scheme, while the discretized equations are solved by SIPSOL method. Coupling between the equations of continuity and momentum is done by SIMPLE algorithm. Under-relaxation method is applied to stabilize the iterative calculation procedure. The comprehensive combustion code was verified by means of the grid-independence study with assessment of numerical error [22].

The comprehensive combustion code was embedded into the in-house developed software with a user-friendly interface, in order to promote using the code by engineering staff dealing with process analysis in utility-scale boiler units. Interface facilitates data input and variation of operation parameters, fig. 1, and enables convergence monitoring, fig. 2.

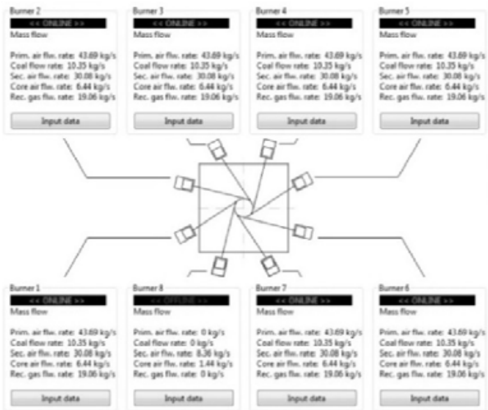

Figure 1. Main form for data input

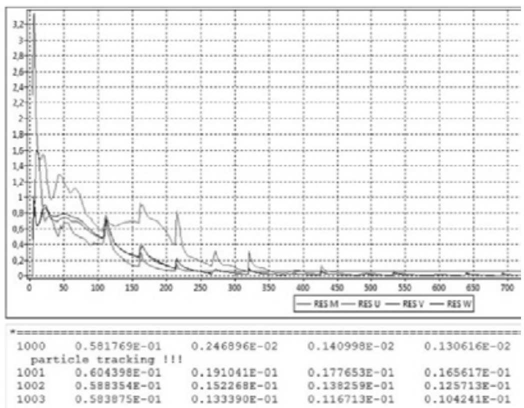

Figure 2. Convergence monitoring panel
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Results and discussion

Operating conditions in the case-study pulverized coal-fired furnace

This numerical study deals with optimization of processes in the water-wall dry-bottom furnace (15.1 m × 15.1 m × 43.0 m) of Kostolac B power plant, tower-type natural circulation pulverized coal boiler units (each of nominal steam capacity 1000 th^{-1} and power output 350 MW_e). The case-study furnace is tangentially fired by eight jet burners, with four tiers each: two lower-stage burners (the main burners, for combustion of larger particle size classes) and two upper-stage burners. The case-study fuel is Serbian lignite Drmno. For standard (nominal) operating conditions at full load seven burners are in operation, total coal and air feed rates are 424.3 th^{-1} and $1050 \cdot 10^3$ Nm^3h^{-1}, respectively. Lower heating value (LHV) for the guarantee coal, as received: 7327 $kJkg^{-1}$; nitrogen content: 0.9%. The pulverized coal moisture content: 8.83%; coal through lower-stage burners (lower/upper tier): 45.5/24.5%, coal through upper-stage burners (lower/upper tier): 19.5/10.5%, secondary air through the lower-stage burners: 68%. Temperature of air-coal dust mixture: 200 °C and secondary air: 288 °C. Residue on sieve: R_{90} = 55% and R_{1000} = 2%. Operating conditions for the nominal regime, the burners arrangement and the fuel are presented in details [7, 21]. Numerical investigations were performed for operating conditions based on the nominal regime, with variation of selected parameters affecting the flow, temperature and gas species concentration fields, as well as the flame and the NO_x emission.

Verification of the computation code and global validation of the comprehensive model

Verification of the numerical code and validation of the model calculations were performed to be able to predict the furnace processes under different and variable operating conditions. The grid independence study suggested using 3-D staggered structured mesh with 549250 nodes, in conjunction with 800 coal particle trajectories per burner in order to achieve convergence, accuracy and calculation efficiency [22]. With respect to the sieve analysis, Rosin-Rammler distribution of particle size classes and repeated numerical experiments, representative initial mean diameter of monodispersed pulverized coal particle was selected ($d_{p,in}$ =150 μm). In addition, simulations were done also for poly-dispersed pulverized coal to point out the impact of combustion of different size classes, defined as given in [23], on the flame within the furnace.

Calculations performed by means of the comprehensive mathematical model were validated against available large-scale measurements in the case-study boiler unit [7, 21-23]. Measurement procedure, equipment and inaccuracy for gas temperature were given in [22]. Repeated measurements of NO content showed good reproducibility, not greater than 5%. Regarding the main subject of the paper, as a kind of global validation of the model, fig. 3 shows comparison between predicted and measured furnace exit gas temperature (FEGT) and NO_x emission from the case-study utility boiler units in a number of measured operation regimes, with the fuel LHV in the range of 8607-9450 kJ/kg, considerably different than the guarantee coal. Difference between predicted and measured NO_x emissions (normal conditions, dry basis, 6% O_2 in flue gases) was 0.2-7.4%, mostly below 4% [7]. It was found that a discrepancy obtained for the B1-2008 test-case might have been attributed to an increased amount of air and/or more nitrogen in the fuel during the experiment compared with the input data in the prediction.

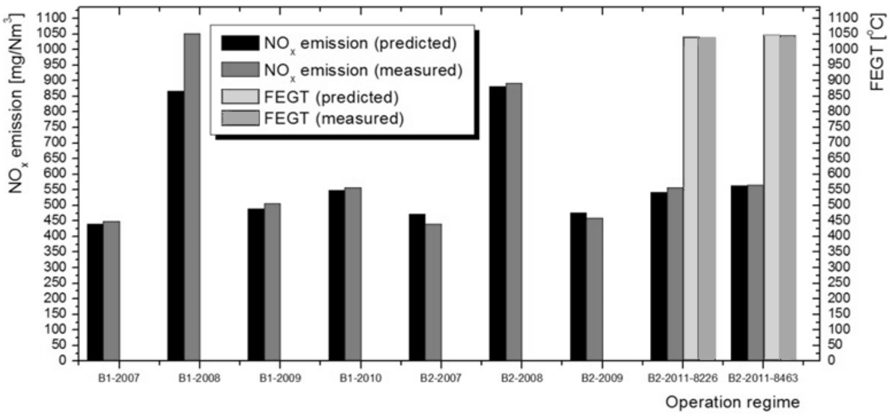

Figure 3. Comparison between predicted and measured FEGT and NO_x emission from the case-study utility boiler furnace of power plant Kostolac B *(for color image see journal website)*

Numerical study on NO_x reduction and flame control by combustion tunings in the furnace

Main objective of the numerical study was twofold: to investigate complex interactions between aerodynamics of two-phase swirling turbulent flow, pulverized coal diffusion flame and chemical reactions related to the coal combustion and nitrogen oxides formation and destruction, as well as to examine implications of these conditions on both the emission and the flame characteristics. Possibilities to reduce the NO_x by means of a proper organization of combustion process were analyzed in conjunction with the entire flow and temperature situations within the case-study furnace. In order to optimize the processes in these respects a number of parameters describing the influences were stressed, such as fuel and air distribution, coal particle size classes and the fuel-bound nitrogen content.

Gas-particle turbulent flow, pulverized coal diffusion flame and NO_x formation/depletion

Previous numerical investigations of processes in the case-study tangentially-fired furnace covered a broad range of operating conditions [3, 7, 21, 22], with an emphasis on the flame vertical and lateral positions [21] and the NO_x emission [3, 7]. These and also further analyzes showed complexity of flow, temperature and gas mixture components concentration fields in dependence on individual parameters. Here, an attempt was made to additionally reveal and clarify some specific, but important aspects of the processes and parameters in interactions.

Although the pulverized coal particle size considerably affects the coal non-premixed flame features, it seems to have been given less attention. The flame geometry and vertical as well as lateral positions for combustion of three particle size classes of monodispersed coal are presented in figs. 4 and 5, for the fuel and air distributed over the burner tiers as given in table 1 for the test-case 11, numerated in accordance with the references showing details on the operating conditions [7, 21]; this also holds for basic numeration of other test-cases analyzed in the work. As clearly demonstrated, the flame shape and location in both sections dramatically change, which influence the heat transfer in the entire space of the combustion chamber. The horizontal cross-section flame geometry follows the usual central vortex flow characteristics for tangential firing [34].

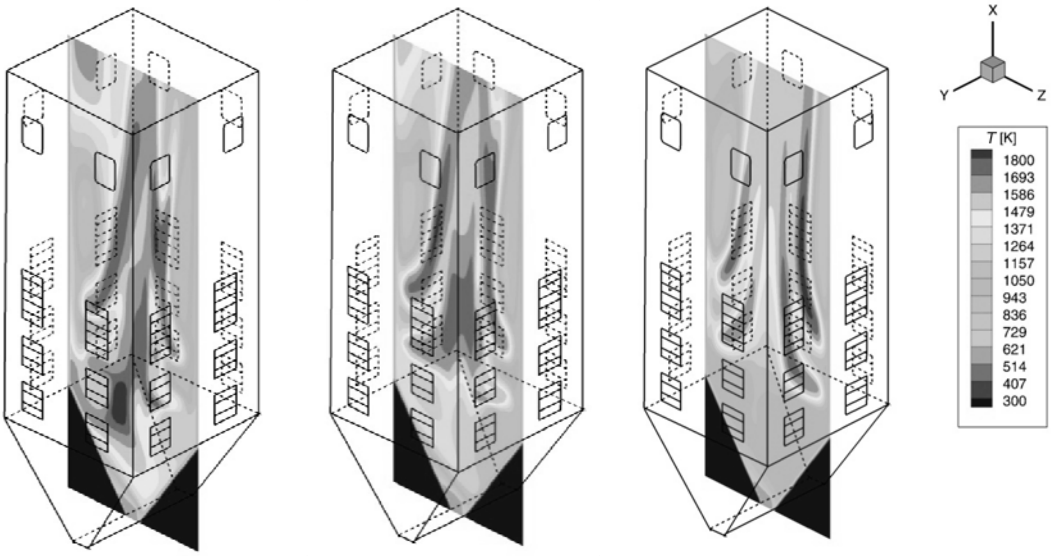

Figure 4. Pulverized coal diffusion flame geometry and vertical position in the furnace, test-case 11 and coal particles size classes 150 µm, 100 µm and 50 µm, respectively *(for color image see journal website)*

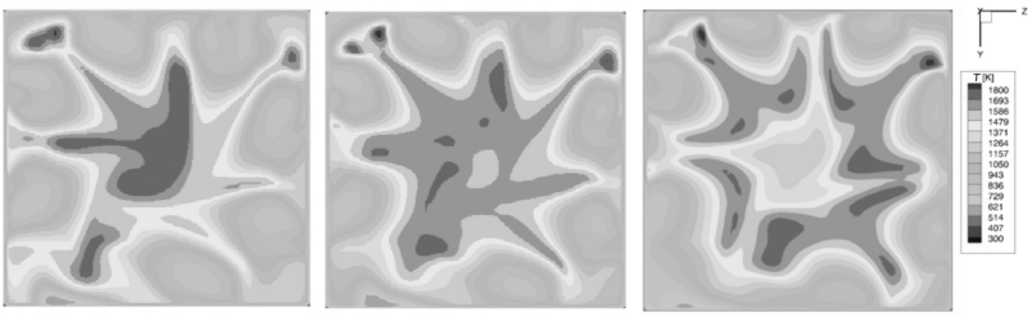

Figure 5. Flame in y-z section through the middle of the main burners (*x* = 14.75 m), test-case 11 and coal particles size classes 150 µm, 100 µm and 50 µm *(for color image see journal website)*

However, instead of commonly formed central "fire-ball", the most finely grinded coal ($d_{p,in}$ = 50 µm) provided a form of a "fire-tube-like" flame geometry, often found in corner or tangential firing of finely pulverized coal. The interesting and to some extent even peculiar flame geometry with a very complex local structure reveals considerably different gas temperature zones in the cross-section, fig. 5, that affect also the local conditions for chemical reactions.

The flame geometry results from the vortex flow in the furnace, intensive turbulent mixing between the fuel and combustion air streams and the coal combustion rates. The gas axial flow field through the lower tiers of the main burners (*i. e.* the lower stage burners) clearly shows a reverse velocity direction in the central region of the cross-section, fig. 6, completely following the central vortex (or, more precisely: central swirling vortex flow) at that level, carrying the particles towards the furnace hopper, fig. 7. The dispersed phase is affected by a strong central vortex flow. The coal particles enter the furnace through different

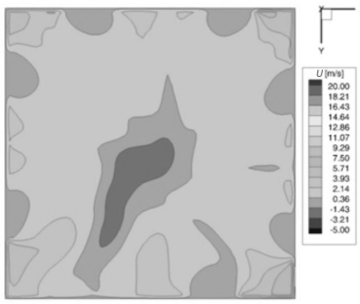

Figure 6. Gas axial flow field in y-z section, lower tiers (x = 12.5 m) of the main burners, test-case 11 and coal particles size class 50 μm
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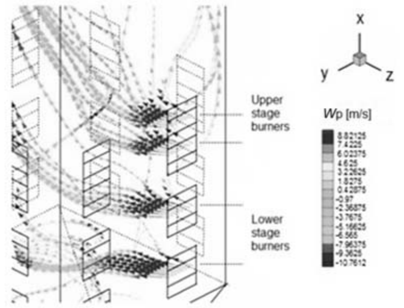

Figure 7. Pulverized coal particles trajectories and the dispersed phase velocity vector field affected by strong central vortex of flue gases
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burner tiers, move predominantly up and disperse over the volume of the combustion chamber, mixing with the air supporting combustion. These processes depend on gas and particles flow rates (and consequently inlet velocities), gas turbulence intensity and inertia of different particle size classes. Some of the larger particles ($d_{p,in}$ = 150 μm) will drop into the furnace hopper, producing higher temperature in that region, fig. 4 (left hand side). In addition, smaller particles (100 μm and 50 μm, compared with 150 μm) are carried more easily by the vortex upward motion of gas and disperse over the wider section, but in the same time combust more rapidly producing hot gases that exchange more energy with the central screen walls and also having a wider diffusion downstream. In combination, all of the processes provide the flame geometry and vertical position as given in fig. 4 (middle and right hand side).

The flow situation will influence the conditions for heterogeneous, as well as homogeneous reactions between chemical species in the field. Very fine coal particles (as for $d_{p,in}$ = 50 μm) are strongly affected by the vortex flow, not fully penetrating the central region of the furnace cross-section, mainly remaining and combusting at the edge of the vortex, thus providing the circle-shaped field of extreme temperatures around the center, fig. 5 (right hand side). The flame geometry entirely corresponds to the fields of axial velocity and oxygen, fig. 8, as well as hydrogen-cyanide and nitric oxide concentration fields, fig. 9, given for the same cross-section at the middle of the main burners through which the majority of both the fuel and secondary air is injected, tab. 1.

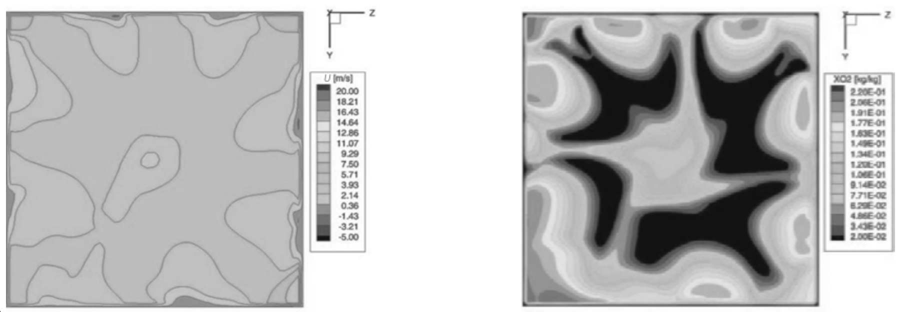

Figure 8. Flue gas axial flow and oxygen concentration fields in y-z section through the middle of the main burners (x = 14.75 m), test-case 11 and coal particles size class 50 μm
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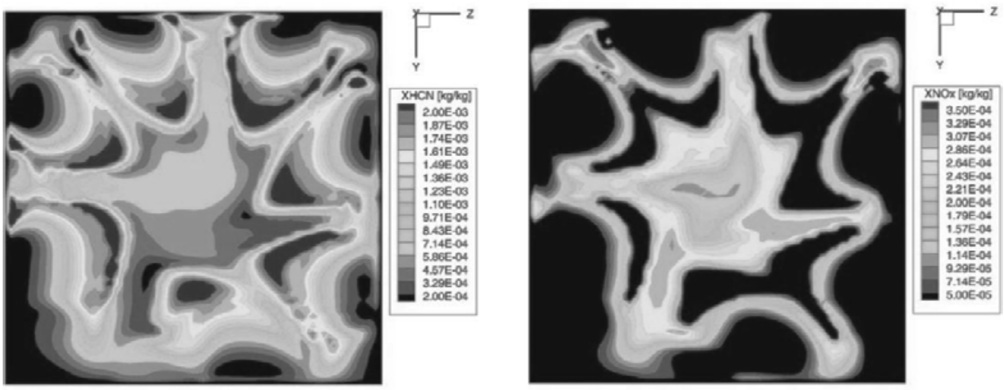

Figure 9. HCN and NO_x concentration fields in y-z section through the middle of the main burners (x = 14.75 m), test-case 11 and coal particles size class 50 μm *(for color image see journal website)*

Table 1. FEGT and NO_x for different coal/air distributions and the coal-bound nitrogen contents

Test-case	Coal distribution over the burner tiers [%]				Secondary air, lower-stage burners* [%]	Fuel-bound nitrogen, as received [%]	FEGT [°C]	NO_x emission [$mgNm^{-3}$]
	Lower-stage burners		Upper-stage burners					
	Lower tiers	Upper tiers	Lower tiers	Upper tiers				
TC1-N1	45.5	24.5	19.5	10.5	67.8	0.90	1029	428
TC1-N2	45.5	24.5	19.5	10.5	67.8	0.34	1029	277
TC1-N3	**45.5**	**24.5**	**19.5**	**10.5**	**67.8**	**0.44**	**1029**	**320**
TC3-N1	30.4	25.8	30.7	13.1	74.2	0.90	1093	468
TC11-N1	40.0	50.0	4.5	5.5	74.2	0.90	996	345
TC11-N2	40.0	50.0	4.5	5.5	74.2	0.34	995	232
TC11-N3	**40.0**	**50.0**	**4.5**	**5.5**	**74.2**	**0.44**	**995**	**263**
TC19-N1	34.9	49.1	6.2	9.8	60.0	0.90	991	320
TC19-N2	**34.9**	**49.1**	**6.2**	**9.8**	**60.0**	**0.34**	**991**	**212**
TC19-N3	**34.9**	**49.1**	**6.2**	**9.8**	**60.0**	**0.44**	**991**	**242**

* Rest of the secondary air through the upper-stage burners

Moreover, in spite of high local temperatures of the gas mixture, fig. 5, and high local content of HCN, as the main source of NO released from the fuel by devolatilization, in the circle zone around the central one, there is not substantial concentration of NO, fig. 9. The reason can be found in relative absence of oxygen in the very zone, already depleted by intensive combustion reactions. In contrast, there is more oxygen, but thus also more NO in the central region of the cross-section, obtained by oxidizing only a part of HCN released from the fuel injecting and mixing with the air flow field within this location. So, in order to control the NO_x emission, it is crucial to tune properly both the amount and the injection location of the fuel and oxidizer (air) and adjust the local fuel/air ratio.

In addition, it is interesting to explore what happens with the flame during the combustion of poly-dispersed pulverized coal. Combustion of different coal particle size classes was studied in [21, 23]. To complement the comprehensive analysis given in [23] we have selected here to present fig. 10, showing at which heights of the furnace the combustion of different initial particle size classes is completed (although there is certain incompleteness of combustion in general).When the combustion ends only the particle of flying ash remains, with diameter $d_{p,min}$. This case-study furnace belongs to 210 MW_e TENT A2 boiler unit, tangentially-fired by Serbian lignite Kolubara-Field „D", with the grinding fineness of R_{90} = 73.85% (residue on 90 μm sieve), with percentage distribution of coal particle sizes represented by five size classes, as given in [23] with other operating conditions considered. The largest size class of 850 μm is not shown in fig. 10; a considerable amount of the particles falls into the hopper. The particles change their diameter during the combustion and the smaller particles combustion is finished before that of the larger ones and *vice versa*. In this case of relatively course grinding, the size classes of 145 μm and 350 μm dominate. The point is that the level at which the combustion is finished (or near to be completed) affects the vertical position of the flame within the furnace and, as a consequence, the furnace walls thermal load as well. This kind of dependences can be obtained for typical conditions in the case-study furnace in the form of the set of curves describing the combustion of each case-study coal in combination with the selected percentage distribution of particle size classes. As such, these curve fittings can help a great deal in analysis and efficient predictions or pre-predictions of the flame position along the combustion chamber affecting the entire working situation, including temperature field and emissions, as already explained.

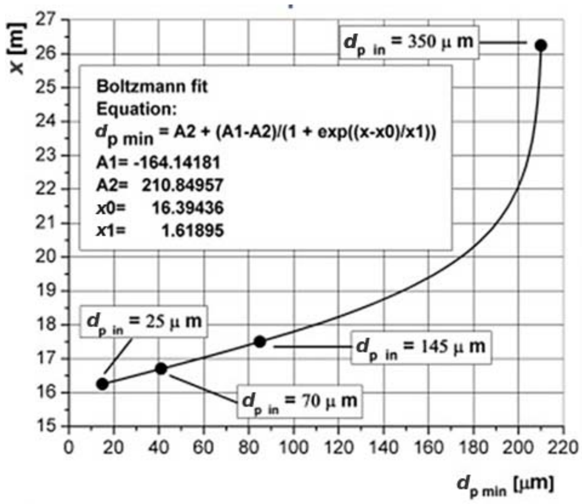

Figure 10. Combustion of different pulverized coal particles size classes finished at different vertical locations along the case-study boiler furnace

Coal and air distribution in the combustion chamber to provide NO_x emission reduction and flame control for different fuel-bound nitrogen content

Effects of different parameters on the NO_x emission from the case-study furnace were investigated in details [3, 7]. Different ways of air and fuel staging to control local excess air (distribution of coal and secondary air over the burners and tiers, overfire air), cold air ingress, grinding fineness and quality of coal, *etc.*, all were found to have important individual or combined influence on the emission and the pulverized coal flame [7, 21]. In brief, increase in the pulverized coal fraction through the main burners (*i. e.* the lower-stage burners) provided a decrease of NO_x emission and FEGT [3]. Injection of about 85-90% of coal through the main burners and 20% less secondary air supplied through the lower-stage burners were recommended to reduce the NO_x emission, individually or in conjunction with the use of overfire air [3, 7]. Uneven distribution of fuel and air over the individual burners, as well as fine grinding of coal can also provide the advantages. Since most primary de-NO_x measures may disturb the boiler operation, adjustments of operating conditions are often required, as also demonstrated [7].

However, the above-mentioned investigations were done for the fuel-bound nitrogen content of 0.9% (as received) just as for the guarantee coal. A fluctuation of the coal quality, including the coal-bound nitrogen content, can often be expected during the boilers operation. So, it was also necessary to examine the influence of the combustion modifications on the emission for different contents of the case-study fuel-bound nitrogen, on the bases of the experiences from exploitation of the boiler units. For some of the most promising test-cases from previous studies [7, 21, 22], the nitrogen content in the fuel was varied (0.34% and 0.44% compared with 0.90%, as received), within the new test-cases given in tab. 1, with uniform operation of seven coal mills as for the nominal test-case 1 and for the coal particle representative mean diameter of 150 μm. As expected, the content of fuel-bound nitrogen decisively determines the NO emission, with considerably different amount of HCN released, fig. 11, and then combusting to form nitric oxide, fig. 12. Table 1 clearly suggests that with a proper tuning of the fuel and air distribution, NO_x emission can reasonably approach the new emission limit of 200 $mgNm^{-3}$, expected to be obligatory from 2023 on. But in assessing the primary measures, other criteria have to be also taken into account, such as FEGT (affecting the boiler efficiency and safety of operation [3, 7]), as well as the necessity for the flame position control [21]. As depicted in fig. 13, due to a large amount of coal injected through the upper-stage burners (44%), there is a potentially dangerous situation with a dramatic increase in FEGT and an excessively high vertical position of the flame that can even enter the convective pass. These conditions can be controlled by injecting more fuel into the lower-stage burners, reducing both the emission and FEGT.

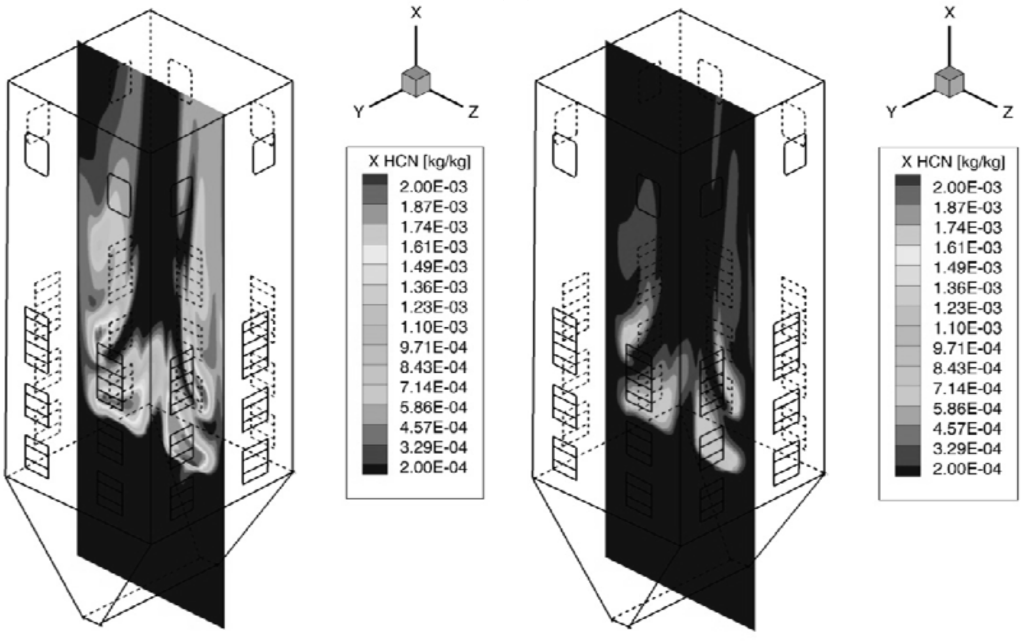

Figure 11. HCN concentration field in the furnace for different content of the fuel-bound nitrogen (0.9% vs. 0.34%, as received), test-cases 19-N1 and 19-N2 *(for color image see journal website)*

Modifications of combustion process offer a great potential for optimizations, but to achieve reliable solutions as much as possible factors have to be included in analysis. In such

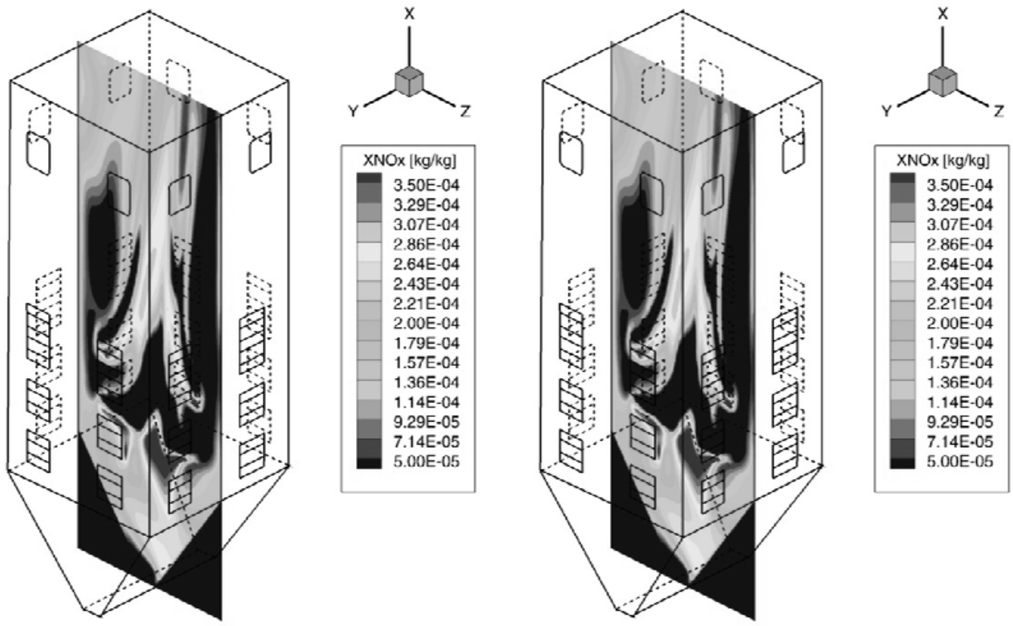

Figure 12. The NO concentration field in the furnace for different content of the fuel-bound nitrogen (0.9% vs. 0.34%, as received), test-cases 19-N1 and 19-N2 *(for color image see journal website)*

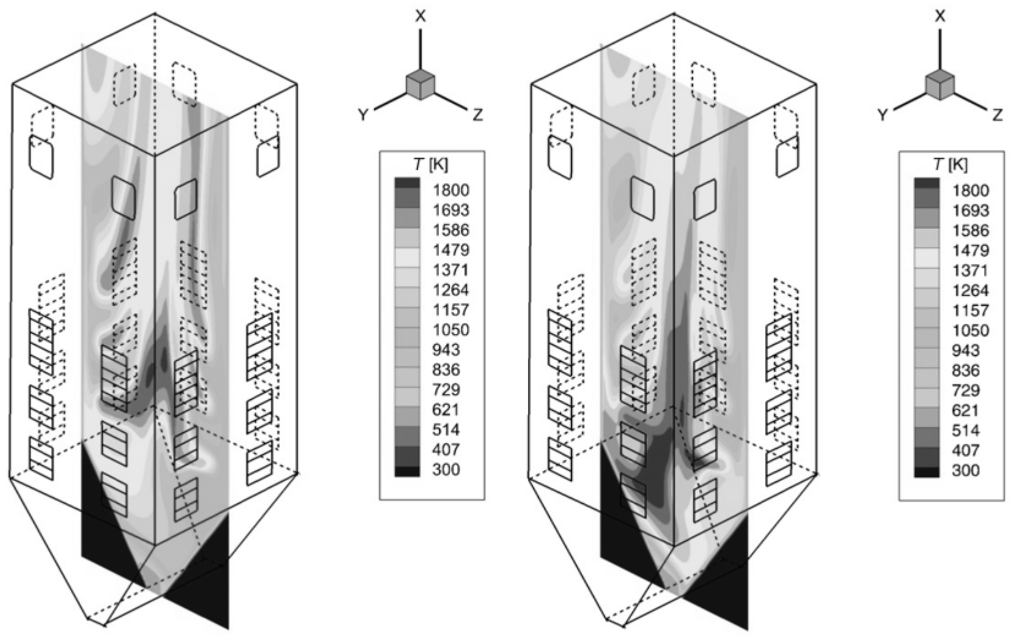

Figure 13. Influence of the fuel distribution over the burner tiers on the temperature field in the test-cases 3-N1 and 1-N1: 56% and 70% of coal through the lower-stage burners, FEGT= 1093 °C **and 1029** °C**, NO_x emission = 468.0 mgNm^{-3} and 428.0 mgNm^{-3}, respectively**
(for color image see journal website)

a way, new and useful ideas may also appear. In addition, when applying the measures for one pollutant control their influences on other pollutants are to be also considered. As shown in [3], the use of furnace sorbent injection (FSI) method to control SO_2 also affected the emission of NO_x due to the influence of the pulverized sorbent transport air injected through the ports above the burners, which changed a bit the flow and temperature fields in the furnace, affecting the conditions for NO_x reactions, like the technique of overfire air. On the other hand, the OFA method was also numerically tested in the case-study furnace, individually and complementing the usual air and fuel staging over the burner tiers [21]. In efforts to attain additional NO_x reduction, the injection of overfire air through the relatively narrow ports (compared with the usual ones), such as those used in FSI method, seems to be advantageous.

The same flow rates of overfire air injected into the ports can provide better penetration towards the center of the flame, intensive mixing with the flue gases and better NO_x reduction effect. Injection of different fractions of secondary air through the special ports above the burners region is examined numerically in tab. 2, compared with the injection through the upper-stage burners instead. For the predicted test-cases, the entire amount of fuel is injected through the main burners (*i. e.* the lower-stage burners), while the upper-stage burner tiers are essentially turned-off. Injection of larger fractions of the secondary air through the special ports promises better NO_x reduction. This kind of both fuel and air distribution over the burner tiers gives 28.4% lower emission in comparison with the combustion organization from tab. 1, of course for the same fuel-bound nitrogen content (compare the test-cases TC21-IP3--N3, tab. 2 and TC1-N3, tab. 1). But again, the overall influence should be assessed also with respect to the FEGT and the flame geometry and position within the furnace. Gas temperature and selected gas mixture components concentration fields are presented in fig. 14, for three characteristic cross-sections. The flame vertical and lateral position, injection of the portion of air through the ports above the burners, release of majority of HCN from fuel devolatilization in the main burners zone, as well as a strong dependence of NO content on oxygen concentration in accordance with the equations (2) and (3), are all clearly depicted.

Table 2. FEGT and NO_x for injection of the secondary air fraction above the main burners

Test-case	Coal distribution over the burner tiers [%]				Secondary air, lower-stage burners* [%]	Fuel-bound nitrogen, as received [%]	FEGT [°C]	NO_x emission [$mgNm^{-3}$]
	Lower-stage burners		Upper-stage burners					
	Lower tiers	Upper tiers	Lower tiers	Upper tiers				
TC20-N1	50.0	50.0	0.0	0.0	90.0*	0.90	1027	376
TC20-IP1-N1	50.0	50.0	0.0	0.0	90.0**	0.90	1020	362
TC20-IP2-N1	50.0	50.0	0.0	0.0	80.0**	0.90	985	338
TC20-IP2-N2	50.0	50.0	0.0	0.0	80.0**	0.34	985	224
TC20-IP1-N3	50.0	50.0	0.0	0.0	90.0**	0.44	1020	277
TC20-IP2-N3	**50.0**	**50.0**	**0.0**	**0.0**	**80.0****	**0.44**	**985**	**252**
TC20-IP1-N3***	50.0	50.0	0.0	0.0	90.0**	0.44	1020	278
TC21-N1	50.0	50.0	0.0	0.0	70.0*	0.90	988	326
TC21-IP3-N1	50.0	50.0	0.0	0.0	70.0**	0.90	958	314
TC21-IP3-N3	**50.0**	**50.0**	**0.0**	**0.0**	**70.0****	**0.44**	**958**	**229**

*Rest of the secondary air through the upper-stage burners; **rest of SA through the injection ports (IP) above the burners, IP1, IP2, IP3: 10%, 20% , 30% of SA; *** distance of SA IP above the burners: 5.25 m, in other IP test-cases 2.79 m

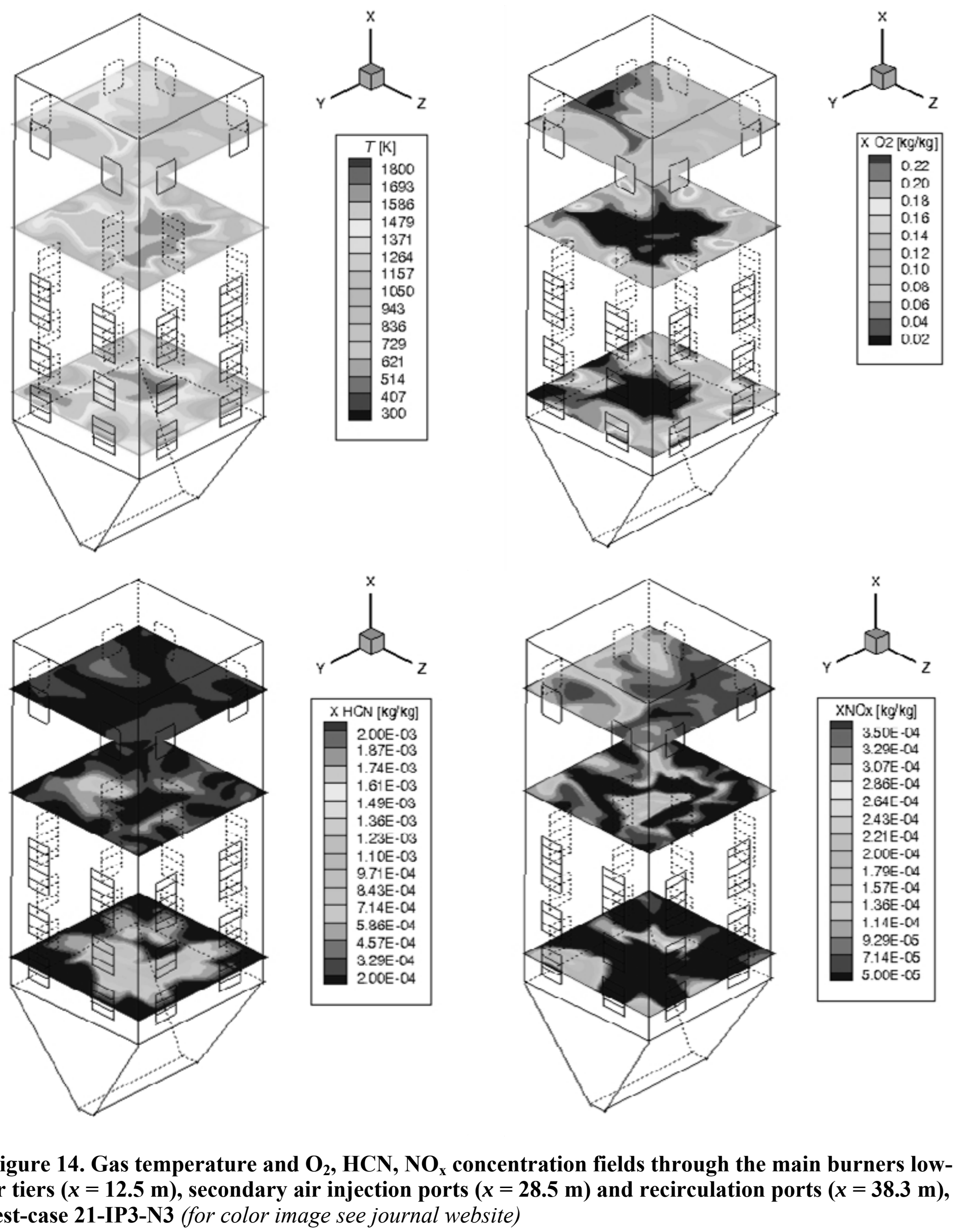

Figure 14. Gas temperature and O_2, HCN, NO_x concentration fields through the main burners lower tiers (x = 12.5 m), secondary air injection ports (x = 28.5 m) and recirculation ports (x = 38.3 m), test-case 21-IP3-N3 *(for color image see journal website)*

In order to take a closer look into the flow field that dominantly affects the mixing processes between the turbulent streams, the velocity vector field and V-velocity component are given in figs. 15 and 16, respectively. The figures relate to the test-case 21-IP3-N3 and the two cross-sections: through the main burners and the secondary air injection ports, that can also be identified in fig. 14. In both sections, there is an obvious displacement of the central vortex towards the wall of the switch-off burner (7 burners are in operation), fig. 15.

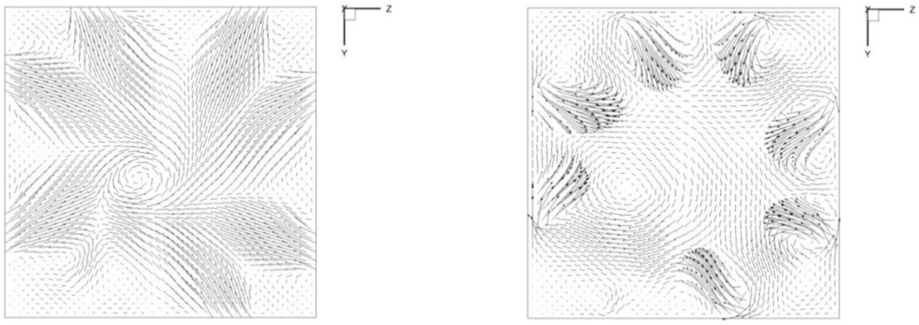

Figure 15. Velocity vector field through the main burners lower tiers (*x* = 12.5 m) and secondary air injection ports (*x* = 28.5 m), test-case 21-IP3-N3

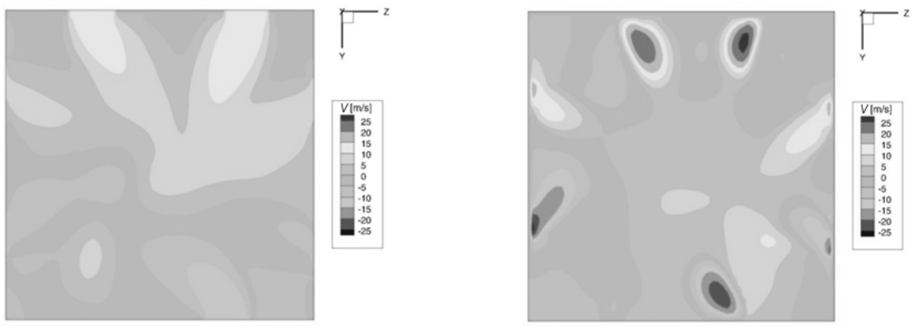

Figure 16. V-velocity component field through the main burners lower tiers (*x* = 12.5 m) and secondary air injection ports (*x* = 28.5 m), test-case 21-IP3-N3 *(for color image see journal website)*

Due to injection of the entire air-coal dust mixture through the main burners there is a considerable amount of fluid mixing at that level with uniformity of the velocity field (figs. 15 and 16, left). Since in this test-case 30% of the preheated (*i. e.* secondary) air enters into the furnace through the ports above the burners, there is also a distinctive vector field at that level (fig. 15, right), promoting turbulent mixing. Moreover, there is also a considerable depth of the fluid injection, due to relatively high-intensity lateral velocity (fig. 16, right). This kind of the flow field distribution between the furnace levels affects the combustion organization in such a way to reduce the NO_x emission, table 2, as well as to stabilize the pulverized coal flame between the levels and mostly in the central regions of the combustion chamber, fig. 14. However, as a result of the central vortex displacement due to the asymmetric mode of the burners operation, fig. 15, the flame is locally approaching the furnace wall which may endanger the screen wall safety due to the ash deposits formation. This effect may be alleviated either by turning-off the burners symmetrically [34], or by fine tuning of fuel and air distribution over the individual burners [21]. In any case, the flow field control appears to be one of the crucial mechanisms to affect the flame, emissions and overall situation in the furnace.

Conclusions

The NO_x emission reduction and pulverized coal flame control by combustion modifications in a tangentially-fired utility boiler furnace were studied numerically for different fuel-bound nitrogen content. An in-house developed differential model of complex gas-

-particle turbulent reactive flow in the case-study furnace was applied to investigate interactions between aerodynamics, diffusion flame and reactions of combustion and NO_x formation/destruction. In order to optimize the processes, a number of parameters were examined, like fuel and air distribution, coal particles size and fuel-bound nitrogen.

The NO formation and depletion were found to be strongly affected by flow, temperature and gaseous components concentration fields. There is a strong dependence of NO content on oxygen concentration. In order to control the NO_x, it is crucial to tune properly both the amount and the injection location of the fuel and oxidizer (air) and adjust the local fuel/air ratio. The pulverized coal flame depends on the central vortex flow in the furnace, turbulent mixing between the fuel and air streams and the coal combustion rates. A specific geometry of the flame with complex local structure affecting the conditions for chemical reactions was obtained for fine grinding of the coal. The flame position during the combustion of poly-dispersed pulverized coal was also examined. Combustion of each particle size class provides different vertical position of the flame. A set of curves describing the combustion of the case-study coal in combination with selected percentage distribution of particle size classes can be obtained and may help in analysis of the flame position along the furnace.

Combustion tunings in the case-study furnace provided around 30% of the NOx emission abatement, approaching the emission limits, with wide possibilities for further improvements in the emission and control of the flame geometry and position (both vertical and lateral). Since fluctuations in coal quality and composition can be often expected, influence of the combustion modifications was also examined for different contents of the case-study fuel-bound nitrogen. As previously demonstrated, injection of about 85-90% of coal through the main burners and 20% less secondary air supplied through the lower-stage burners were recommended to reduce the NO_x emission, individually or in conjunction with the use of overfire air, uneven distribution of fuel and air over the individual burners, as well as fine grinding of coal. In efforts to attain additional NO_x reduction, the injection of overfire air through relatively narrow ports (compared with the usual ones), seems to be advantageous providing better penetration of air jet towards the center of the flame, intensive mixing with the flue gases and better NO_x reduction effect. Combining injection of the entire amount of fuel through the main burners with injection of 30% of the secondary air through the special ports above the burners provided more than 28% lower emission. Injection of the largest fractions of the air--coal dust mixture through the main burners caused the mixing of considerable amount of fluid at that level with uniform velocity field. In general, the flow field control appears to be one of the crucial mechanisms to affect the flame, emissions and overall situation in the furnace. Understanding of the turbulent swirling reactive flow and interactions between the gas--particle two-phase flow aerodynamics, pulverized coal diffusion flame characteristics and related chemical reactions is essential to describe and control the situation in the combustion chamber of the pulverized coal-fired boilers. Complex numerical experiments provide conditions for improvements of the power plant furnaces exploitation regarding efficiency and emissions. For the purpose of efficient and environmentally friendly exploitation of utility boilers under different and variable operating conditions there is a need for more detailed analysis of the processes in interactions.

The comprehensive in-house developed combustion code used for the simulations was embedded into the user-friendly interface to promote using the code not only by scientists but also by engineering staff. Introduction of new chemical mechanisms into the code will enable to assess the performance of additional methods for NO_x control. Improvements of submodels describing individual processes and phenomena will increase overall predictive abilities of the developed model in order to optimize entire complex of flow, as well as heat and mass transfer processes in pulverized fuel-fired furnaces.

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This work was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (project: Increase in energy and ecology efficiency of processes in pulverized coal-fired furnace and optimization of utility steam boiler air preheater by using in-house developed software tools, No. TR-33018).

Nomenclature

A_1 – pre-exponential factor for fuel NO formation rate, [s^{-1}]
d_p – diameter of pulverized coal particle, [m]
R – residue on sieve, [%]
S_Φ – source term for general variable Φ
S_p^Φ – additional source due to particles
T – temperature, [K]
t – time, [s]
U_j – velocity components, [$m\ s^{-1}$]
X – mass fraction, [$kg\ kg^{-1}$]

Greek symbols

α – coefficient in fuel NO formation rate, [–]
Γ_Φ – transport coefficient for gen. variableΦ
ε – emissivity, [–]
ρ – density, [$kg\ m^{-3}$]
Φ – general variable
χ – mole fraction, [$mol\ mol^{-1}$]

Subscripts

g – gas
in – initial
min – minimal
p – particle
w – wall

Acronyms

FEGT – furnace exit gas temperature
FSI – furnace sorbent injection
IP – injection port
LHV – lower heating value
OFA – overfire air
SA – secondary air
SOFA – separated overfire air
TC – test-case

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