MODELING AND OPTIMIZATION OF PROCESSES FOR CLEAN AND EFFICIENT PULVERIZED COAL COMBUSTION IN UTILITY BOILERS

by

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Pulverized coal-fired power plants should provide higher efficiency of energy conversion, flexibility in terms of boiler loads and fuel characteristics and emission reduction of pollutants like nitrogen oxides. Modification of combustion process is a cost-effective technology for NO_x control. For optimization of complex processes, such as turbulent reactive flow in coal-fired furnaces, mathematical modeling is regularly used. The NO_x emission reduction by combustion modifications in the 350 MW_e Kostolac B boiler furnace, tangentially fired by pulverized Serbian lignite, is investigated in the paper. Numerical experiments were done by an in-house developed 3-D differential comprehensive combustion code, with fuel- and thermal-NO formation/destruction reactions model. The code was developed to be easily used by engineering staff for process analysis in boiler units. A broad range of operating conditions was examined, such as fuel and preheated air distribution over the burners and tiers, operation mode of the burners, grinding fineness and quality of coal, boiler loads, cold air ingress, recirculation of flue gases, water-walls ash deposition and combined effect of different parameters. The predictions show that the NO_x emission reduction of up to 30% can be achieved by a proper combustion organization in the case-study furnace, with the flame position control. Impact of combustion modifications on the boiler operation was evaluated by the boiler thermal calculations suggesting that the facility was to be controlled within narrow limits of operation parameters. Such a complex approach to pollutants control enables evaluating alternative solutions to achieve efficient and low emission operation of utility boiler units.

Key words: *modeling, pulverized coal combustion, NO_x emission reduction, furnace, utility boiler efficiency*

Introduction

In order to meet challenging tasks of environmental-friendly development, present-day coal utilization technologies have to enable efficient energy conversion, reduction of pollution and flexibility in terms of boiler loads and fuel quality, increasingly important in domestic power plants. Both the emission reduction and the combustion efficiency increase are essential in retrofitting the power plants to extend their operational life expectancy. For

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achieving these improvements based on optimization of complex processes in furnaces and boilers during exploitation, mathematical modeling is regularly used [1-17].

Since nitrogen oxides are identified as direct precursors of photochemical smog and contribute to acid rain, considerable efforts focus on modeling NO_x formation/destruction in pulverized coal combustion [5-10, 12, 18, 19]. Although NO_x emission from Serbian plants firing low-rank coals-lignites is not extremely high, it considerably exceeds new European emission limits. Primary measures-combustion modifications offer a simple and cost effective means of NO_x reduction [19], in contrast to post-combustion clean-up. Investigation [2] focused on testing the NO_x model over a variety of coal type, firing configurations and boiler power outputs. Some authors simulated tangentially-fired furnaces [1, 5, 8, 11, 12, 15], while others considered wall fired furnaces [3, 6, 7, 9, 10]. Some predictions were performed to obtain data that could be used to minimize unburned coal in fly ashes [17]. Most of the authors predicted nitric oxide (NO) only [6, 10, 12, 17], as the most abundant NO_x from coal combustion. Majority of simulations neglected prompt NO, while considering fuel NO that typically accounts for 75%-95% of the total NO in coal combustors [19, 20] and thermal NO [6, 9, 10, 17] significant at the flame temperatures greater than 1600-1800 K [19]. Authors mostly tried to verify some of primary methods for NO_x reduction, optimizing the combustion process. Multiple stage combustion showed good NO_x reduction [6-10]. Flue gas recirculation (FGR) proved to be effective and economical method for reducing NO_x emission [21]. New burners [4, 6, 7, 17], overfire air (OFA) systems [3, 8], or alternatives like horizontal bias combustion [1] were examined as well.

Reduction of NO_x emission by primary measures was investigated in tangentially-fired furnace of Kostolac-B 350 MW_e boiler units. The analysis was done by an in-house developed 3-D differential model of furnace processes (with the fuel- and thermal-NO formation/destruction sub-model), validated against available large-scale measurements in the case-study boiler units [13-16]. The code was designed to be easily used by engineering staff dealing with the process analysis in boiler units, offering a proper balance between sophistication of sub-models describing individual processes and user-friendly data-input. Optimization of complex processes within the pulverized coal-fired furnace, both with respect to the emission and the efficiency, was performed over a very wide range of operating conditions, taking into account not only extremely complex interactions of influencing parameters but also their effect on the entire boiler unit operation. Individual or combined effects of a number of operation parameters were studied, such as coal and preheated air distribution over the burners and the burner tiers, grinding fineness and quality of coal, boiler loads, cold air ingress, recirculation of flue gases and water-walls ash deposition. It was also essential to provide proper characteristics of the pulverized coal flame, because of its impact on heat transfer in the furnace and thermal load of the water walls [14]. Such kind of de-NO_x measures may reduce the boiler efficiency and disturb safe operation of superheaters, which was also investigated.

Mathematical model

The comprehensive differential model of two-phase turbulent reactive flow in pulverized coal-fired utility boiler furnace at stationary conditions was described in details [13-16]. Two-phase flow is treated by Eulerian-Lagrangian approach. 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:

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

with additional sources due to particles S_p^{Φ}, while ρ, U_j, Γ_Φ, and S_Φ are gas-phase density [kgm^{-3}], velocity components [ms^{-1}], transport coefficient and source term for general variable Φ, respectively. To close the eq. (1), k-ε turbulence model is used. Dispersed phase is described by differential equations of motion, energy and mass change in Lagrangian field. Particle velocity vector is a sum of convective and diffusion velocity. Effect of particles on gas phase is accounted for by PSI Cell method. Continuity equation for particle number density is given in the form of eq. (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 ε_g = 0.35 and ε_w = 0.85 [22]. Calculation procedure for prediction of the furnace walls ash deposits impact on the radiative heat exchange was also developed [23] 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 described with respect to the char combustion (by far slower process compared with devolatilization and oxidation of volatiles), within the *shrinking core* concept. Change of the coal particle mass, equal to the reaction rate, is given in combined kinetic-diffusion regime [13-15]. Mass and heat addition due to combustion is considered by the sources due to particles in eq. (1). The case-study lignite Drmno kinetic parameters were determined in vertical cylindrical laboratory furnace [13, 14]. This approach may be easily adjusted to include additional heterogeneous, as well as homogeneous reactions, like in [24]. Initial and boundary conditions usual for elliptical partial differential equations are applied. Conditions near the walls are described by the *wall functions*. Discretization of partial differential equations is performed by control volume method and hybrid-differencing scheme. Discretized equations are solved by SIPSOL method. Coupling of continuity and momentum equations is done by SIMPLE algorithm. Stabilization of iteration procedure is provided by under-relaxation. The comprehensive combustion code was verified by grid-independence study with assessment of numerical error [13].

The NO_x formation and destruction reactions sub-model was incorporated into the complex combustion code. Simplified chemical models in conjunction with detailed CFD calculations were used for the reasons of practicality. The thermal NO formation/destruction reactions can be predicted by Zeldovich expression with respect to a single reaction rate constant [19]. The NO_x sub-model comprises also the fuel NO formation/depletion reactions [25-27] 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 [28]. Nitrogen released within NH_3 is taken into account through equivalent nitrogen content. The chosen model of NO formation is in conjunction with De Soete global-reaction kinetics [26, 27].

Fuel NO formation reaction rate is given as:

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

Coefficient $0 < \alpha < 1$ depends on the local concentration of oxygen [26]. As proposed by Lockwood and Romo-Millares [19] for fuel-lean conditions that prevail in pulverized coal-fired furnaces, preexponential factor A_1 is increased by 3.5 compared with original value $A_1 = 1$ (De Soete [26], more proper for fuel-rich conditions). The best fit, based on experimental NO emission values, was found to be $3.5 \cdot 10^{10}$ L/s [18] and was extensively used for NO_x predictions in utility scale boilers [9, 10]. In this work, calculations were performed with different values of preexponential factor A_1 depending on local conditions. For NO depletion rate the expression has been selected according to the literature [25], as a function of mole fractions: χ_{HCN}, χ_{O_2}, and χ_{NO}. Partial differential equations for NO and HCN are solved in Eulerian field, eq. (3). The source of NO, S_{NO}, is obtained in dependence on the total net formation/destruction rate of NO, while the source of HCN, S_{HCN}, comprises both the HCN release by devolatilization and HCN depletion in the gaseous phase. Mass fractions of NO and HCN are given by X_{NO} [kgkg^{-1}] and X_{HCN} [kgkg^{-1}], respectively, while Γ_{NO} and Γ_{HCN} are corresponding transport coefficients. The NO_x sub-model is described in details and validated by comparisons with available emission measurements on the case-study boiler units [15].

$$\begin{aligned} \frac{\partial}{\partial x_j}(\rho U_j X_{NO}) &= \frac{\partial}{\partial x_j}\left(\Gamma_{NO}\frac{\partial X_{NO}}{\partial x_j}\right) + S_{NO}, \\ \frac{\partial}{\partial x_j}(\rho U_j X_{HCN}) &= \frac{\partial}{\partial x_j}\left(\Gamma_{HCN}\frac{\partial X_{HCN}}{\partial x_j}\right) + S_{HCN} \end{aligned} \tag{3}$$

The in-house developed software is to be used primarily by engineering staff dealing with the process analysis in boiler units. An easy-to-use interface facilitates variation of operation parameters, turning on/off individual burners, introducing input data and convergence monitoring.

Results and discussion

The case-study utility boiler units Kostolac B1 and B2 (nominal steam capacity 1000 t/h and power output 350 MW_e at full load, each) are of tower-type with natural circulation. The water-wall dry-bottom furnaces (dimensions: 15.1 m × 15.1 m × 43.0 m), with after combustion device-grate, are identical. The furnace, burning pulverized coal-Serbian lignite Drmno, 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. In standard (nominal) operating conditions at full load seven burners are in operation, total coal and air feed rates are 424.3 t/h and $1050 \cdot 10^3$ Nm^3/h, respectively. The guarantee coal lower heating value (LHV), as received: 7327 kJ/kg; 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%. Air-coal dust mixture temperature: 200 °C, secondary air temperature: 288 °C. Residue on sieve: $R_{90} = 55\%$ and $R_{1000} = 2\%$. Numerical investigations were performed for nominal operating conditions, but also for measured test-case with the fuel having LHV, as received: 8463 kJ/kg. Operating conditions for the nominal regime and the measured test-cases, with arrangement of the burners are presented in details [14, 15].

For reliable predictions in variable operating conditions, verification of the numerical code and validation of the model calculations were performed. In order to achieve convergence, accuracy and calculation efficiency, the grid independence study suggested using 3-D staggered structured mesh with 549250 nodes, in conjunction with 800 coal particle trajectories per burner [13]. Representative initial mean diameter of monodispersed pulverized coal particle was selected (d_p = 150 μm), regarding the sieve analysis, Rosin-Rammler distribution of particle size classes and repeated numerical experiments. The comprehensive model was validated against available large-scale measurements in the case-study boiler units [13-16]. Measurement procedure, equipment and inaccuracy for gas temperature were given in [13]. Repeated measurements of NO content showed good reproducibility, not greater than 5%. Difference between predicted and measured NO_x emissions (normal conditions, dry basis, 6% O_2 in flue gases) was 0.2-7.4%, but mostly below 4% [15].

Numerical study on NO_x reduction by combustion modifications in the case-study furnace

The model was applied after validation to study NO_x emission reduction by proper combustion modifications in the case-study furnace, regarding also the furnace exit gas temperature (FEGT) and the pulverized coal flame. Impacts of many parameters were analyzed individually, or in combination. Previous detailed investigations demonstrated considerable NO_x reduction by proper distribution of fuel and air over the burners and tiers, control of local excess air and finer grinding of coal [14, 15]. In this study, water-walls ash deposits impact was pointed out as well. Additional and more complex conditions such as different boiler loads and recirculation of flue gases were also carefully studied.

Fuel and combustion air distribution, cold air ingress, grinding fineness, and quality of coal

A number of test-cases considered the same values of coal and preheated air flow rates, in total and per burner, with uniform operation of seven coal mills, as for the nominal conditions-test case 1 (TC1), selected as the reference one and presented separately to closely describe the NO formation/destruction process [13-15]. The contribution of thermal NO was of the order of several percents of the total NO. In contrast to thermal NO, the content of fuel NO is less affected by temperature, but strongly by nitrogen content in the fuel and the excess air, *i. e.* oxygen concentration.

Influence of pulverized coal distribution over the burner tiers on FEGT and NO_x emission is shown in fig. 1. In general, the results suggest that the increase of the pulverized coal fraction through the lower-stage (*i. e.* main) burners provides a decrease of both FEGT and NO_x emission, while the flame is descending. In more details: for 86.4% of pulverized

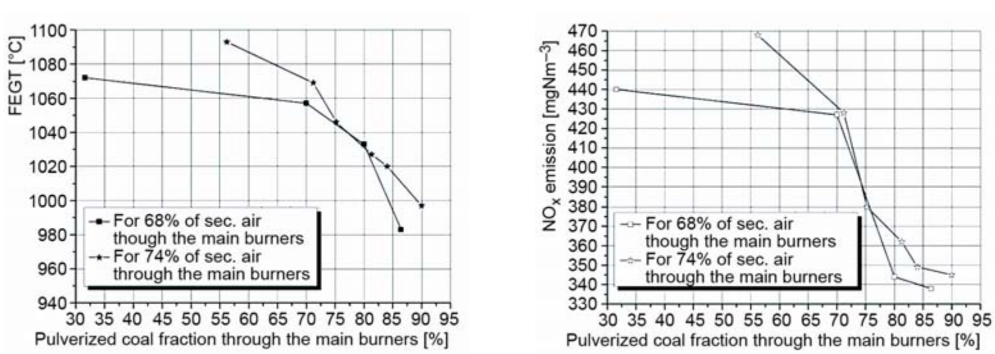

Figure 1. Influence of the fuel and combustion air distribution over the burner tiers on FEGT (left) and NO_x emission (right) from the case-study boiler furnace

coal supplied to the lower-stage burners, NO_x emission reduction of 18.6% was predicted, while for 90% of coal through the lower-stage burners 16.9% of the emission reduction [15], depending also on secondary air distribution over the burner tiers. In addition, fig. 1 presents the influence of the secondary air fraction through the main burners. Less secondary air supplied through the lower-stage burners means more air through the upper-stage burners, so the combustion is to some extent postponed into the higher regions of lower local temperatures where NO formation is less intensive, providing lower emission. For example, a difference in secondary air through the lower-stage burners (60% instead of 74.2%), gave decrease in FEGT and the emission reduction of 22.8% and 8.1% with respect to TC1, respectively [15]. Uneven distribution of fuel and air over the individual burners provides lower FEGT and higher emission, than in the TC1, but only to some extent. However, the flame is nearly centered [15], which is to decrease the water-walls thermal stresses and diminish the conditions for fouling and slagging. Predictions showed a considerable influence of the cold air ingress; although for the same distribution of coal and air NO_x emission only slightly changed, FEGT was decreased to such an extent that it was impossible to achieve guaranteed parameters of steam. Increase in the share of cold air ingress in the total amount of air from 9% to 20% caused 50 °C decrease in FEGT. There is often a fluctuation of the coal quality during the boiler operation, so different coal quality was also investigated: guarantee coal for the mill, lower guarantee quality and upper guarantee quality, compared with the guarantee coal (for the boiler) in the reference test-case. As expected, the fuels with different LHV provided completely different temperature and NO_x concentration fields [15].

Table 1. FEGT and NO_x emission for different grinding fineness of coal

Test-case	Initial coal particle size d_p [μm]	FEGT [°C]	NO_x emission [mgNm^{-3}]
TC1	150	1029	428
TC1-100	100	1018	396
TC1-50	50	994	426
TC5	150	1020	349
TC5-100	100	1020	363
TC5-50	50	1010	431
TC11	150	997	345
TC11-100	100	1007	353
TC11-50	50	1014	418
TC28*	150	993	343
TC28*-100	100	1003	354
TC28*-50	50	1007	410

* Burners operating unevenly

Grinding fineness of coal was studied through the variation in initial particle size of monodispersed pulverized coal particles with diameters: d_p = 50 μm and 100 μm, compared with d_p = 150 μm, tab. 1, for selected test-cases, numbered in accordance with previous studies with details on the test-cases operating conditions [14, 15], if needed. With respect to the TC1, finer grinding (d_p = 100 μm) provided slightly lower NO_x emission, but d_p = 50 μm gave a slight increase in the emission. However, in the rest of the examined test-cases, different change of NO_x emission was obtained. This might be attributed to the complexity of mixing between gases and coal of different grinding, considering also differences in the rest of operating conditions. Final conclusions would require more profound analysis of this complex process. In addition, different geometry of the flame and FEGT were predicted for different grinding fineness of coal [14]. Figures 2 and 3 show the flame geometry and

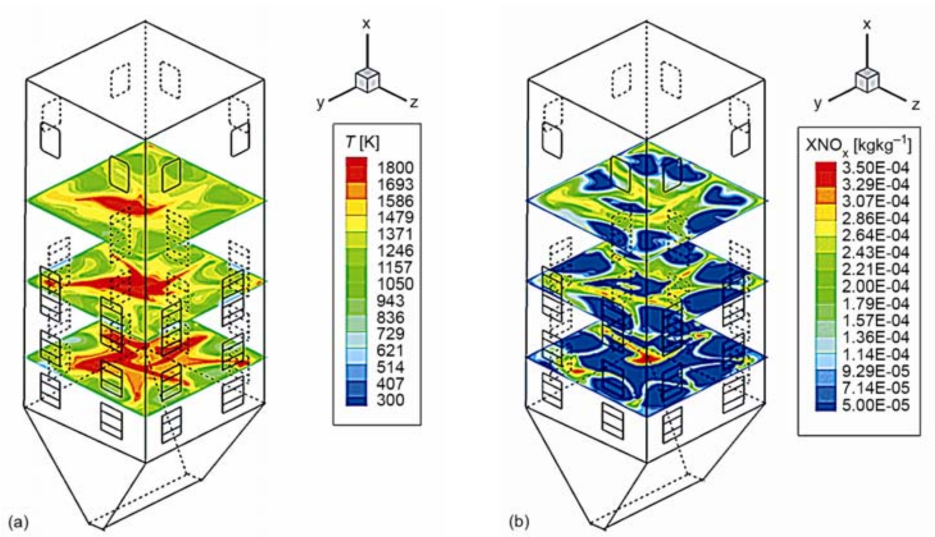

Figure 2. Flame geometry and NO_x field for test-case 1-100 (coal particles size 100 μm)

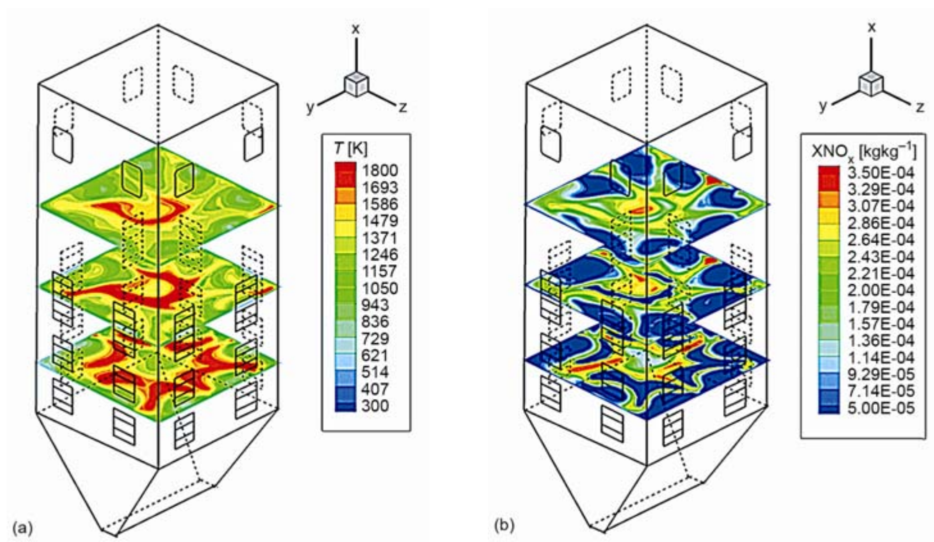

Figure 3. Flame geometry and NO_x field for test-case 1-50 (coal particles size 50 μm)

NO_x content. The fineness corresponding to 50 μm provided characteristic flame geometry in the form of *firetube*, typically found in tangential firing of very fine grinding of coal, instead of usual *fireball* in the furnace center. Affecting the mixing between coal, air and flue gas in the burners region, this phenomenon considerably change the entire NO_x field and, consequently, the emission.

In addition, combined effect of different operation parameters was examined. In the TC28, characterized by uneven operation mode of the burners providing favorable, nearly centered flame position [15], significant emission reduction was also achieved, 25.8% compared with TC1, tab. 1. When there was also finer grinding of coal (d_p = 100 μm, instead of 150 μm) and 20% of secondary air was redirected from lower- to upper-stage burners, the emission reduction was even 30% compared with the TC1, although FEGT was somewhat decreased. The uneven operation mode of the burners did not provide negative effects on both the emission and FEGT.

Since most de-NO_x measures based on combustion modifications reduce boiler efficiency and/or disturb operation of superheaters and reheaters, additional adjustments of the boiler conditions are required [29]. An analysis was performed by thermal calculations of the case-study boiler at full load for guarantee coal on the basis of predicted FEGT for most promising test-cases [15]. At higher FEGT amounts of heat received by the third stage of superheater and the second stage of reheater (final stages regarding the steam flow) were increased. In order to keep the superheated and reheated steam temperature at 540 °C water should be injected into the steam pipelines. At the FEGT below 990 °C it was impossible to achieve required superheated steam temperature, but reheated steam temperature was attained in any test-case considered. Effects of increased amount of water injected into reheated steam are higher fuel consumption and reduced boiler efficiency. The boiler exit gas temperature and the efficiency did not change significantly in dependence on the FEGT. Optimal range of FEGT was 995-1010 °C (*i. e.* 990-1010 °C), with respect to the attainment of required superheated steam temperature and minimal water injection into the reheated steam pipeline [15].

Pulverized coal ash deposition on the water-walls (slagging) reduces the heat exchange between the flame and the walls, increasing FEGT, and also NO_x emission, as predicted for nominal conditions of Kostolac B boiler unit. Regarding the effect of the ash deposits, numerical simulations can help to optimize temperature and flow conditions within the furnace [23]. The flue gas temperature increase will increase heat transfer to the convective pass and amount of water injected into the superheated and reheated steam pipeline and, consequently, reduce the boiler efficiency. Slagging is accompanied by fouling in the convective pass. For the water-walls deposit thickness of 4 mm and 10% increase in fouling, thermal calculations showed the boiler efficiency 1% less than with no slagging and fouling.

Influence of different load of the case-study boiler on FEGT and NO_x emission

During the utility boilers exploitation, it is important to enable wide load range over a wide fuel range, and a stable operation with minimal use of additional fuel for start-up. Low-load operation modes of the boiler help to achieve these tasks. Table 2 shows FEGT and NO_x emission in different loads of the case-study boiler. Selected test-cases are numbered in accordance with previous studies [14, 15].

As expected, partial load modes: 85% and 70% of the full-load provided lower FEGT compared with the full-load operation. The NO_x emission increased in the partial load modes due to the complex influences of the operation mode change on flow field, flame and chemical reactions. Figure 4 shows three characteristic cross-sections within the furnace (through both the lower-stage and the upper-stage burners and between the burners and the recirculation ports) for three loads of the boiler. The flame geometry and temperature field are quite similar for 85% and 100% of the full load (and consequently also the flow and concentration fields). In contrast, at 70% of the full-load, six burners in operation instead of seven

Table 2. The FEGT and NO_x for different boiler loads

Test-case	Full load – 100%		Partial load – 85%		*Partial load – 70%	
	FEGT [°C]	NO_x at furnace exit [$mgNm^{-3}$]	FEGT [°C]	NO_x at furnace exit [$mgNm^{-3}$]	FEGT [°C]	NO_x at furnace exit [$mgNm^{-3}$]
TC1	1029	428	1022	440	974	444
TC5	1020	349	1013	358	971	384
TC6	1033	344	1029	354	972	362
TC11	995	345	993	355	951	378
TC19	991	320	989	333	955	347
TC28	993	343	993	344	945	365

* 6 burners in operation (2 burners turned off; for the rest of the cases 7 burners in operation)

ones for the other two operation modes provided completely different flow, temperature and concentration fields, with strong centrally positioned vortex within the furnace, exerting an influence also on NO_x emission. Figures 5 and 6 presents gas streamlines for 85% and 70% of the boiler load in the same cross-sections as given in fig. 4. Large, as well as medium size vortices promote strong turbulent mixing between fuel, air and flue gases and intensive chemical reactions mainly in central region, while smaller vortices bring about some dead zones around, figs. 5 and 6.

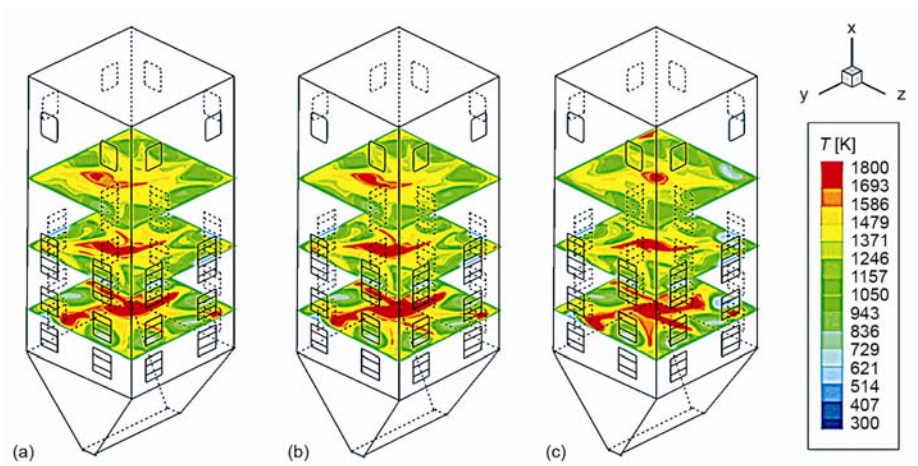

Figure 4. Flame in the test-case 1, for full (100%) and partial loads (85% and 70%) of the case-study boiler unit, cross-sections at *x* = 14.75 m, 22.50 m, and 30.75 m

There is an evident impact of the flow field on the gas mixture components concentration fields, figs. 7 and 8, and, consequently, on the NO formation/destruction reactions. In addition, the nitric oxide content within the furnace follows the gas temperature field, but even more the oxygen and the hydrogen cyanide concentration fields, as shown at the cross-sections in figs. 7 and 8, because the fuel NO, obtained from oxidation of the hydrogen cyanide, is a predominant form of nitrogen oxides during pulverized coal combustion.

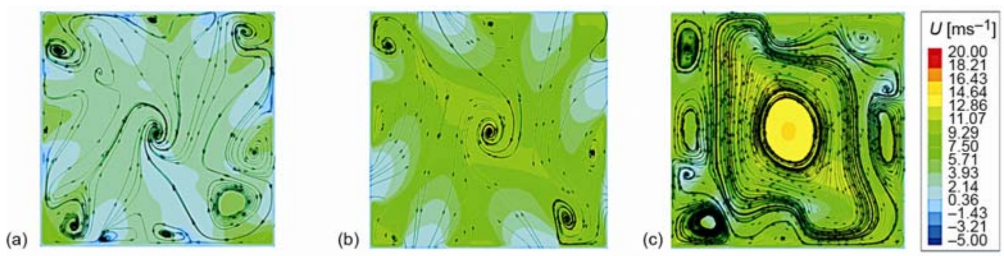

Figure 5. Flue gas flow field in y-z section at *x* = 14.75 m, 22.50 m, and 30.75 m, test-case 1, partial load (85%) of the case-study boiler unit, 7 burners in operation

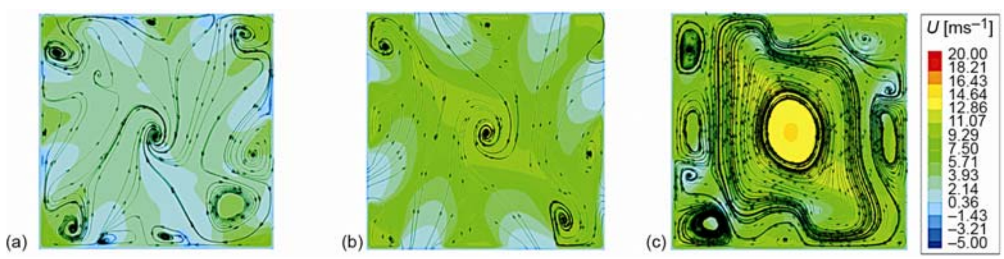

Figure 6. Flue gas flow field in y-z section at *x* = 14.75 m, 22.50 m, and 30.75 m, test-case 1, partial load (70%) of the case-study boiler unit, 6 burners in operation

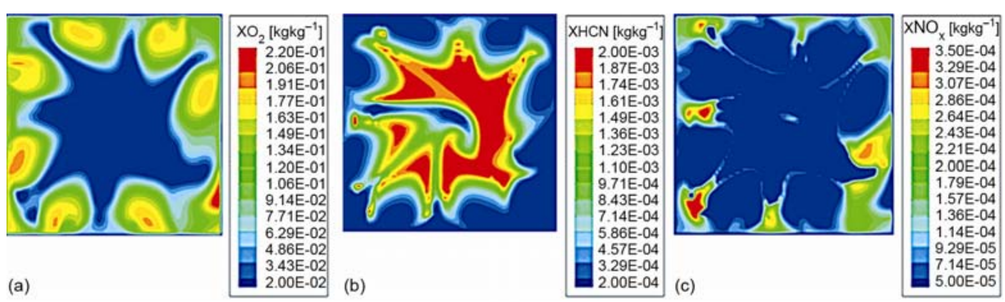

Figure 7. Oxygen, HCN, and NO_x fields in y-z section through the lower-stage burners (*x* = 14.75 m), test-case 1, partial load (85%) of the case-study boiler unit

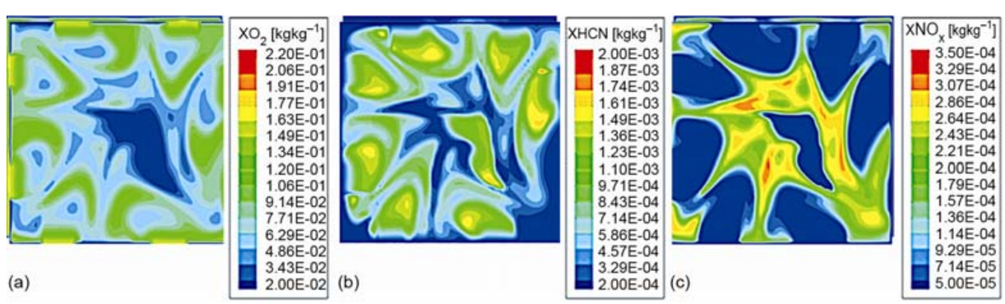

Figure 8. Oxygen, HCN, and NO_x fields in y-z section through the upper-stage burners (*x* = 22.50 m), test-case 1, partial load (85%) of the case-study boiler unit

Flue gas recirculation for NO_x control in full and partial load conditions

In order to lower the combustion temperature which limits NO_x emission the flue gases are often recirculated from the boiler exit into the burners region. Oxygen content in the combustion zone also decreases due to the mixing between preheated air and recirculated gases, attenuating the reaction of NO_x formation. Boilers operate with FGR rates of 0-30% [21].

Table 3 presents selected results of numerical predictions and thermal calculations for variations of the measured test-case LHV8463 (LHV = 8463 kJ/kg, as received, FGR rate is 4.9% of total amount of the boiler exit flue gases) in the Kostolac B boiler unit [15]. For this case, a very good agreement was obtained between predicted and measured values for FEGT and NO_x emission. Subject of the investigation was the effect of both the FGR rate and the boiler load on NO_x reduction, FEGT and the boiler efficiency. Test-cases LHV8463-4 and LHV8463-8 (4% and 8% of FGR) compared with LHV8463-0 (0% of FGR) showed that increase in FGR cooled the furnace gases and decreased FEGT, providing also a decrease in NO_x emission (23.4% for 8% of FGR), but the boiler exit gas temperature increased and the boiler efficiency decreased. Due to increased flow of flue gases through the boiler during FGR the amounts of water injected to control the superheated and reheated steam temperatures increased, also reducing the boiler efficiency. In the test-cases with reduced boiler load (85% of the full load) FEGT decreased, while NO_x emission increased probably due to the disturbance of flow, temperature and combustion conditions under the partial load. The NO_x reduction efficiency decreased for the partial load, but only slightly and this change was less for higher FGR rate. So, in the examined test-cases, effects of FGR on NO_x emission were not disturbed considerably by reduced boiler load.

Table 3. NO_x emission control by FGR in different loads of the case-study boiler unit

Test-case	FEGT [°C]	Boiler efficiency coefficient for full load [%]	NO_x emission [mgNm^{-3}]	NO_x reduction with respect to none FGR [%]
LHV8463-0 (FGR = 0%), full load	1087	86.56	748.0	-
LHV8463-0, 85% of load	1077	-	763.3	-
LHV8463-4 (FGR = 4%), full load	1057	86.14	642.7	**14.1**
LHV8463-4, 85% of load	1048	-	672.6	**11.9**
LHV8463-8 (FGR = 8%), full load	1028	85.74	569.1	**23.9**
LHV8463-8, 85% of load	1021	-	585.6	**23.3**
*LHV8463 (FGR = 4.9%, as in nominal regime), full load, **predicted/measured**	**1047/1045**	85.79	**564.2/565.3**	**24.6**
*LHV8463, 85% of load	1024	-	587.9	**23.0**

* Seven mills in operation and cold air ingress 20% into the furnace (in the rest of the cases six mills in operation and the cold air ingress 13%, as in nominal regime)

Conclusions

Combustion modifications affecting the NO_x emission, the FEGT and the flame in 350 MW_e Kostolac boiler pulverized coal fired furnaces were investigated by an in-house developed and validated model. Individual and combined effects of different parameters were examined, such as fuel and preheated air distribution over the burners and tiers, grinding fineness and quality of coal, cold air ingress, water-walls ash deposition, the case-study boiler load and recirculation of flue gases.

The emission reduction of up to 30% could be achieved only by proper organization of combustion process in the existing furnace, with improvement of FEGT and the flame position. The following combustion modifications could be proposed: about 85% of pulverized coal introduced through the lower-stage burners; local excess air control in the burners region by redirecting up to 20% of secondary air from the lower- to the upper-stage burners; finer grinding of coal in combination with less preheated air through the lower-stage burners. Combination of uneven fuel and air distribution over individual burners, proper distribution over the burner tiers and finer grinding of coal offered a favorable, centered flame position with lower NO_x emission. The boiler thermal calculations were performed for guarantee coal to examine whether the most promising test-cases disturbed the boiler efficiency, suggesting an optimal range of FEGT providing the safe operation of superheaters and reheaters. Pulverized coal ash deposits reduce heat transfer to the furnace water-walls, increase FEGT and NO_x emission and reduce the boiler efficiency, as also demonstrated by the calculations.

The boiler operation modes: 85% and 70% of the full-load provided lower FEGT. The flame geometry and temperature field for 70% of the full-load, with six burners in operation instead of seven ones, provided considerably different situations in the furnace. The flow field for different boiler loads exerted a strong influence on the NO formation/destruction reactions. The NO content was also affected by the gas temperature, but even more by O_2 and HCN fields influencing the fuel NO as a predominant form of NO_x in pulverized coal combustion.

Increase in flue gas recirculation from the boiler exit into the burners region decreased FEGT and also NO_x emission (23.4% of NO_x reduction for 8% of FGR), but the boiler exit gas temperature increased and the boiler efficiency decreased. In the test-cases considered, the effect of FGR on NO_x emission was disturbed under reduced boiler load conditions, but not considerably.

The developed software proved to be an efficient numerical tool for optimization of complex processes in the coal-fired furnaces under a wide range of operating conditions. Further improvements of sub-models will additionally increase abilities of the comprehensive code. There is a need for more detailed analysis of operating conditions like different grinding fineness of coal and variable boiler loads, for the purpose of efficient and environmentally friendly exploitation of power plants.

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Nomenclature

A_1 – preexponential factor for fuel NO formation rate, [s^{-1}]
d_p – initial 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, [ms^{-1}]
X – mass fraction, [$kgkg^{-1}$]

Greek symbols

α – coefficient in fuel NO formation rate, [–]
Γ_Φ – transport coefficient for general variable Φ
ε – emissivity, [–]
ρ – density, [kgm^{-3}]
Φ – general variable
χ – mole fraction, [molmol^{-1}]

Subscripts

g – gas
p – particle
w – wall

Acronyms

LHV – lower heating value
FEGT – furnace exit gas temperature
FGR – flue gas recirculation
OFA – overfire air

References

[1] Zhang, X., *et al.*, Numerical Investigation of Low NO_x Combustion Strategies in Tangentially Fired Coal Boilers, *Fuel*, *142* (2015), Apr., pp. 215-221
[2] Chui, E. H., Gao, H., Estimation of NO_x Emissions from Coal-Fired Utility Boilers, *Fuel*, *89* (2010), 10, pp. 2977-2984
[3] Liu, H., *et al.*, Effect of Two-Level Over-Fire Air on the Combustion and NO_x Emission Characteristics in a 600 MW Wall-Fired Boiler, *Numerical Heat Transfer. Part A: Applications*, *68* (2015), 9, pp. 993-1009
[4] Zhou, H., *et al.*, Numerical Simulation of the Combustion Characteristics of a Low NO_x Swirl Burner: Influence of the Primary Air Pipe, *Fuel*, *130* (2014), Avg., pp. 168-176
[5] Fan, J., *et al.*, Modeling of Combustion Process in 600 MW Utility Boiler Using Comprehensive Models and its Experimental Validation, *Energy & Fuels*, *13* (1999), 5, pp. 1051-1057
[6] Zeng, L., *et al.*, Numerical Simulation of Combustion Characteristics and NO_x Emissions in a 300 MW_e Utility Boiler with Different Outer Secondary-Air Vane Angles, *Energy & Fuels*, *24* (2010), 10, pp. 5349-5358
[7] Chen, Zh., *et al.*, Gas/Particle Flow and Combustion Characteristics and NO_x Emissions of a New Swirl Coal Burner, *Energy*, *36* (2011), 2, pp. 709-723
[8] Modlinski, N., Computational Modeling of a Utility Boiler Tangentially-Fired Furnace Retrofitted with Swirl Burners, *Fuel Processing Technology*, *91* (2010), 11, pp. 1601-1608
[9] Coelho, L. M. R., *et al.*, Application of a Global NO_x Formation Model to a Pulverized Coal Fired Boiler with Gas Reburning, *Proceedings,* 4th International Conference on Technologies and Combustion for a Clean Environment, Lisbon, 1997, Paper 9.4
[10] Xu, M., *et al.*, Modelling of the Combustion Process and NO_x Emission in a Utility Boiler, *Fuel*, *79* (2000), 13, pp. 1611-1619
[11] Khalilarya, Sh., Lotfiani, A., Determination of Flow Pattern and its Effect on NO_x Emission in a Tangentially Fired Single Chamber Square Furnace, *Thermal Science*, *14* (2010), 2, pp. 493-503
[12] Diez, L. I., *et al.*, Numerical Investigation of NO_x Emissions from a Tangentially-Fired Utility Boiler under Conventional and Overfire Air Operation, *Fuel*, *87* (2008), 7, pp. 1259-1269
[13] Belošević, S., *et al.*, Numerical Study of a Utility Boiler Tangentially-Fired Furnace under Different Operating Conditions, *Fuel*, *87* (2008), 15-16, pp. 3331-3338
[14] Belošević, S., *et al.*, Numerical Prediction of Pulverized Coal Flame in Utility Boiler Furnaces, *Energy & Fuels, 23* (2009), 11, pp. 5401-5412
[15] Belošević, S., *et al.*, Numerical Analysis of NO_x Control by Combustion Modifications in Pulverized Coal Utility Boiler, *Energy & Fuels*, *26* (2012), 1, pp. 425–442
[16] Belošević, S., *et al.*, Three-Dimensional Modeling of Utility Boiler Pulverized Coal Tangentially Fired Furnace, *International Journal of Heat and Mass Transfer*, *49* (2006), 19-20, pp. 3371-3378
[17] Hashimoto, N., *et al.*, Numerical Analysis of Pulverized Coal Combustion in a Multiburner Furnace, *Energy & Fuels*, *21* (2007), 4, pp. 1950-1958
[18] Lockwood, F. C., Romo-Millares, C. A., Mathematical Modeling of Fuel NO Emissions from PF Burners, *Journal of the Institute of Energy*, *65* (1992), pp. 144-152
[19] Hill, S. C., Smoot, L. D., Modeling of Nitrogen Oxides Formation and Destruction in Combustion Systems, *Progress in Energy and Combustion Science*, *26* (2000), 4-6, pp. 417-458
[20] Smoot, L. D., Smith, P. J., *Coal Combustion and Gasification*, Plenum Press, New York, USA, 1985

[21] McAdams, J. D., Minimize NO_x Emissions Cost-Effectively, *Hydrocarbon Processing*, *80* (2001), 6, pp. 51-58
[22] Blokh, A. G., Thermal Radiation of a Pulverized-Coal Flame, in: *Heat Transfer in Steam Boiler Furnaces*, Hemisphere Publishing, New York, USA, 1988, pp. 85-124
[23] Crnomarković, N., *et al.*, Numerical Investigation of Processes in the Lignite-Fired Furnace when Simple Gray Gas and Weighted Sum of Gray Gases Models are Used, *International Journal of Heat and Mass Transfer, 56* (2013), 1-2, pp. 197-205
[24] Belošević, S., *et al.*, A Numerical Study of Pulverized Coal Ignition by Means of Plasma Torches in Air–Coal Dust Mixture Ducts of Utility Boiler Furnaces, *International Journal of Heat and Mass Transfer, 51* (2008), 7-8, pp. 1970-1978
[25] Solomon, P. R., Colket, M. B., Evolution of Fuel Nitrogen in Coal Devolatilisation, *Fuel*, *57* (1978), 12, pp. 749-755
[26] de Soete, G. G., Overall Reaction Rates of NO and N_2 Formation from Fuel Nitrogen, *Proceedings of the Combustion Institute*, *15* (1975), 1, pp. 1093-1102
[27] de Soete, G. G., Heterogeneous N_2O and NO Formation from Bound Nitrogen Atoms during Coal Char Combustion, *Proceedings of the Combustion Institute*, *23* (1991), 1, pp. 1257-1264
[28] Stojiljković, D., *Nitrogen Oxides During Combustion of Domestic Lignites* (in Serbian), Andrejevic Foundation, Belgrade, 2001
[29] Li, S., *et al.*, NO_x Emission and Thermal Efficiency of a 300 MW_e Utility Boiler Retrofitted by Air Staging, *Applied Energy*, *86* (2009), 9, pp. 1797-1803

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