AIR STAGING APPLICATION EFFECTS ON OVERALL STEAM BOILER OPERATION

by

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This paper presents the results of calculation system of main processes in power steam boiler, before and after application of air staging. Modified air injection scheme was implemented during 2015 on the power steam boiler within unit 1 of TPP Kostolac B. Measurements performed on site showed that applied reconstruction led to a permanent loss of the steam boiler power. This study was performed in order to define the cause of such an occurrence and to consider the possibility for regaining the designed steam parameters along with keeping NO_x concentration in prescribed limits. This paper discusses the influence of repositioning the air injection location on processes within the furnace. Furthermore, the influence of the redistribution of injected air-flow along the furnace height on important boiler operation parameters has been analyzed.

Analysis showed that, with appropriate dosing of air along the height of the existing furnace, it is possible to achieve the optimum of the boiler's operation parameters. Results of research showed that air staging throughout the furnace height in best test case additionally reduces NO_x concentration (195-225 mg/Nm^3) and increases the power of considered boiler (828.8-751.1 MW) with an insignificant decrease of the boiler's efficiency (86.27-86.77%). Furthermore, the designed temperatures of superheated (540-498 °C) and reheated (540-518 °C) steam have been reached again, whereby the safety of the boiler's operation has been significantly increased.

Results of this study improve the present explanation of the processes occurred in the furnace with applied primary measures. They also give directions on defining the most influential parameters on considered processes with the final purpose to increase the efficiency and availability of the entire plant.

Key words: *air staging, power steam boiler, NO_x, sub-stoichiometric*

Introduction

The Republic of Serbia belongs to the group of states that exploit coal out of domestic sources and do not plan to reduce its utilization in near future. Over 80% of fossil fuel reserves belong to low caloric lignite. More than 75% of overall coal reserves are located in the Kosovo-Metohija complex. Currently exploited significant reserves in Serbia are located in the Kolubara (14.0%) and Kostolac (3.0%) complex. Important reserves in form of non-utilized potential are located in the Sjenica and Kovin complex (2.7%). Currently, the power production system in Serbia with its capacities is able to maintain the balance between electricity production and overall consumption. Due to significant reserves in solid fossil fuel, stability in power production in the future will rely on utilization of lignite [1]. According to the previously accepted

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development strategy of power production sector, revitalization of all larger power production units is being performed. Expansion of the existing capacities in sense of building new lignite-fired units is also planned. Reconstruction of units in operation and building new units will be guided so that rigorous ecological standards stated in obligatory European legal acts are fulfilled.

The NO_x, pollutants emitted in atmosphere by various human actions, are mostly generated by combustion of fossil fuels in power production plants [2, 3]. Concentration of NO_x in flue gases within power production units in Serbia which operate in design conditions, significantly exceeds prescribed limitation of 200 mg/Nm^3 (dry, 6% O_2) [4]. As generation of NO_x mostly depends on nitrogen content in fuel and local concentration of free oxygen [5], in order to reduce its formation, it is important to control conditions occurred within the furnace during fuel combustion. In accordance with that, primary measures present the dominant and preventive mean by which combustion of pulverized coal can be organized in order to negatively accelerate the nitrogen oxides' formation process [6]. Most applied measures able to provide low concentration of free oxygen in combustion zones are air staging [7] and recirculation of cold gases [8].

Existing engineering procedures for estimation of boiler operation parameters are developed to be used in the case of designing boilers that operate in conventional conditions where oversaturated combustion is performed. Such calculation procedures are inappropriate to be used in the case of analyzing the boiler operation with applied air staging system. Investigating effects of new combustion schemes' application has been performed by linking calculation procedures of the differential model of processes in the furnace with integral calculation procedures for predicting operation of all heating surfaces within the boiler as well as the boiler as a whole. Such a calculation system, previously verified and validated, is published in [9]. Due to the synergy of its differential model and integral calculation method, it provides a possibility to estimate the boiler's operational characteristics with combustion obtained mostly in sub-stoichiometric zones. Using this procedure, it is possible to vary many parameters in order to obtain a wider overview of quality of all considered power boiler operation regimes with applied air staging system.

In this paper, results of effects of replacing the location of air injection throughout the furnace height, as well as air-flow injected for post-combustion on processes within the furnace, have been presented. Also, the change of fuel introduction stage and availability of the boiler to achieve the designed steam parameters in new operation conditions has been considered.

Steam boiler calculation system

In the purpose of estimating the operational quality of the boiler entirety, methodology of linking calculation procedures of its elements has been applied. The used calculation system implies the application of numerical methods for obtaining a solution of the complex equation system of the stationary turbulent reactive two-phase radiative flow within the domain, where combustion of pulverized coal takes place. Gained results linked with operational characteristics of other elements within the boiler can be used for the quantification of occurred changes in order to depict its influence on operation of other heating surfaces. Such an approach provides a possibility to obtain a more detailed approximation of the intensity of combustion process, heat transfer as well as the mechanisms of formation and destruction of NO_x. The 3-D calculations are performed in the commercial software package ANSYS Fluent. The used software ensures state values of reactive components as well as the heat transfer towards boundary planes of the domain - furnace walls. Such a calculation procedure implies performing and combining results of thermal calculation of boiler, numerical calculation of the furnace and aerodynamic calculations of air and mill tract. The presented calculation system, along with its synergy, ensures the algorithm which allows a firm base for testing measures which influence the overall boiler functionality regardless of the applied combustion scheme.

Although there are numerous published papers considering this topic, most of them analyze the possibility of utilization of new mathematical models and primary measures [10-14] for the purpose of achieving appropriate decreases in nitrogen oxides concentration [15-17]. This leaves the influence of the air staging system application on main processes within the furnace unexplored. One of the main aims of overall research, which is partially published in this paper, is to use such a method in generating confident and efficient procedures for testing the influence of the air staging system application on existing boiler plants. Considering the effects of selected primary measures on the functionality, efficiency and ecological performance of the existing boiler in operation, the possibility to extend the lifetime of existing plants might be more closely examined.

Analysis after air staging system application

In order to achieve operation with lower concentration of NO_x, combustion system on steam boiler within unit 1 of TPP Kostolac B has been reconstructed during 2015 so that the primary measure was implemented. By application of the new combustion scheme, a modified system for preparation of pulverized coal and jet burners has been retained. Changes have been made in the air injection system so that, after the reconstruction, air is blown into the furnace on two additional stages, fig. 1. The applied modification ensured combustion to be obtained in sub-stoichiometric conditions in a larger part of the considered furnace volume. This led to the reduction in boiler's power, which is reflected through the impossibility of the boiler to achieve designed parameters of the superheated and reheated steam. Although new conditions provided reduction in NO_x concentration, as well as the increase in boiler's efficiency, the regulation area was completely lost.

In order to eliminate negative effects of applied modifications, this study analyzes possibilities to retrieve designed steam parameters along with retaining the reduced concentration of NO_x in flue gases. In accordance with that, five characteristic cases of air staging organization have been considered (reconstructed boiler – R). The air injection location, the air flow and the distribution of fuel introduced along the furnace height have been varied.

Designed combustion configuration before the reconstruction has been taken as a reference basic case (unreconstructed boiler – UNR). In such a combustion scheme, the furnace operated with the permanent excess air ratio of 1.22. The modified system for pulverized coal preparation is organized so that the air mixture is divided in two streams before it is introduced in the furnace. Primary current with 70% of coal dust is introduced via main burners, while the rest is blown through vapor burners. Distribution of gaseous and solid phases has been adopted in accordance with working conditions on site, as it is shown in tab. 1. Within the designed configuration, main and vapor burners axes are located in the horizontal plane. Parallel overview of gained calculation results for the designed operation regime and all other considered cases is given in the following tables.

The test case 1 (TC1) presents the configuration obtained after the reconstruction on site during 2015. After the modification, distribution of the excess air ratio is changed. New arrangement was established in order 0.96-1.01-1.15, from the burners level toward the furnace outlet, respectively. The first stage of the air injection is located on 37.5 m height. Here, air is injected through nozzles located on the furnace walls. This configuration of the first stage of air injection is retained through all test cases with the applied air staging system (TC1-TC4). The second air stage (OFA 2) is applied by means of nozzles located on 48.0 m height at the side of furnace walls directly ahead the furnace outlet. Axes of main and vapor burner was inclined for 15° towards the furnace hopper.

In the TC2 case, distribution of excess air ratio is retained in respect to the TC1 case, while OFA 2 is relocated and positioned at 51.4 m height. Air injection has been performed by use of lances on which a large number of nozzles is located. Lances are positioned in the center horizontal cross-section of the last superheater stage, first heating surface after the furnace outlet in respect to the flue gas stream. Slope of burners' axes has been also retained.

The TC3 configuration corresponds to the TC2 with all previously described settings included, except the slope of main burner axis. In this case, axis is positioned in a horizontal plane.

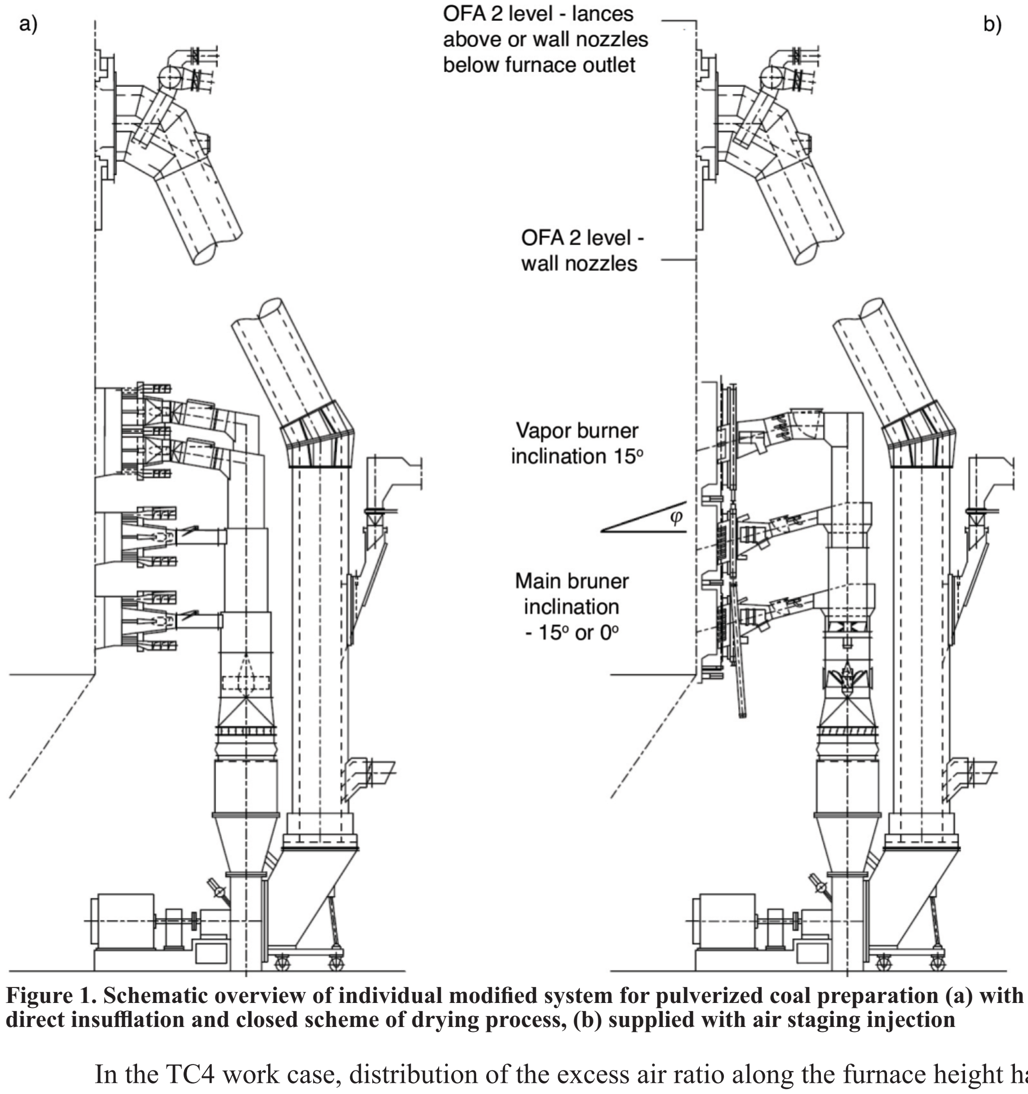

Figure 1. Schematic overview of individual modified system for pulverized coal preparation (a) with direct insufflation and closed scheme of drying process, (b) supplied with air staging injection

In the TC4 work case, distribution of the excess air ratio along the furnace height has been changed. Here, in respect to the air injection stages, this parameter is set according to the order 0.90 - 0.98 -1.15. Slope of all burners axes has been retained from the TC1 case.

After the modification made during 2015, jet burners have been adopted so that the separation rate of the gaseous phase of air mixture is retained. Coal dust distribution after the air mixture classifier was changed, where 80% was introduced via main burners and the rest was blown trough vapor burners as it is shown in tab. 1. Nominal steam production for all considered cases was 1060 per hours of the superheated steam. The low heat value (LHV) of used coal was 8373.6 kJ/kg. Ultimate and proximity analysis of utilized fuel is presented in [18].

Air staging application effects on furnace processes

In fig. 2, temperature fields in selected cross-sections of the furnace in the case of air staging application are shown. All previously described configurations (form TC1 to TC4) have been considered. It can be noted that, *n* case of TC1, high temperature zones are narrower, while flue gases' local temperatures are lower. Such an occurrence can be explained by reduced coal consumption in preset working conditions. It can also be noted that energy introduced in the furnace is higher in every following considered case. Also, such growth of energy is followed by the increase of flue gas temperature in the entire calculation domain. This leads to the conclusion that propagation of the combustion process by increasing the height of OFA 2 position in the TC2 test case provides an increase of the overall furnace heat load. Increase in fuel introduction height by modifying the slope of burners in TC3 provides same trends of changes. This effect is most influential in TC4 test configuration, where the combustion process is additionally delayed, and larger portions of fuel are burned with a lower air dosing in the furnace. Considering a comparative overview arranged in fig. 3, mentioned differences in temperature fields within selected horizontal cross-sections can be more efficiently noted. It is especially important to emphasize that the air staging configuration was influenced by the temperature of flue gases at the furnace outlet. Consequently, the amount of heat transferred by radiation in the last stage of the superheater placed at the furnace outlet is also modified. Last superheater stage is a semi-radiative type of heating surface, which implies that its operation and working conditions can provoke a significant impact on the state of the superheated steam at the boiler outlet. It can be also stressed that the increase in the height of the last stage of air dosing ensures a possibility to

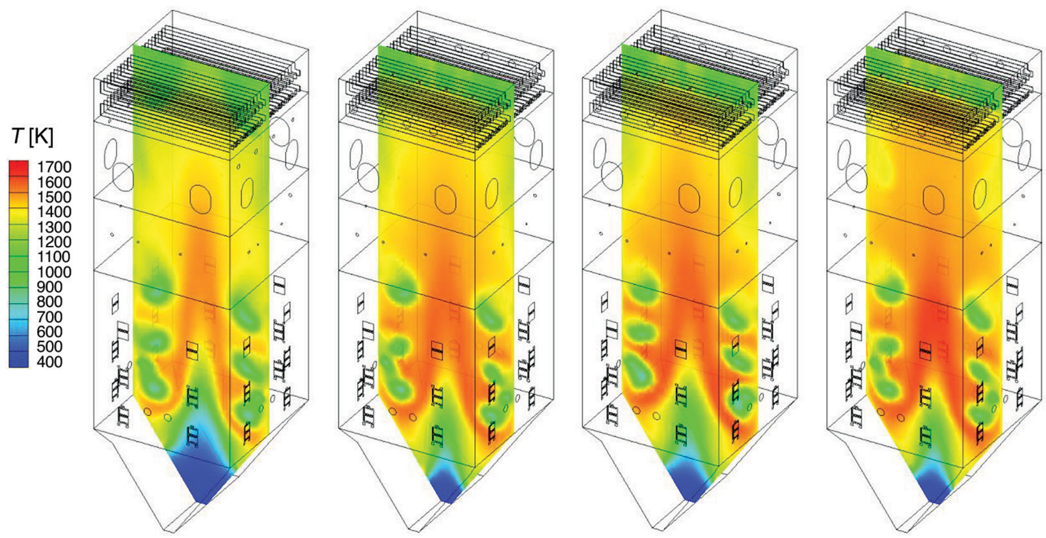

Figure 2. Temperature fields in central vertical cross-section of furnace for TC1-TC4

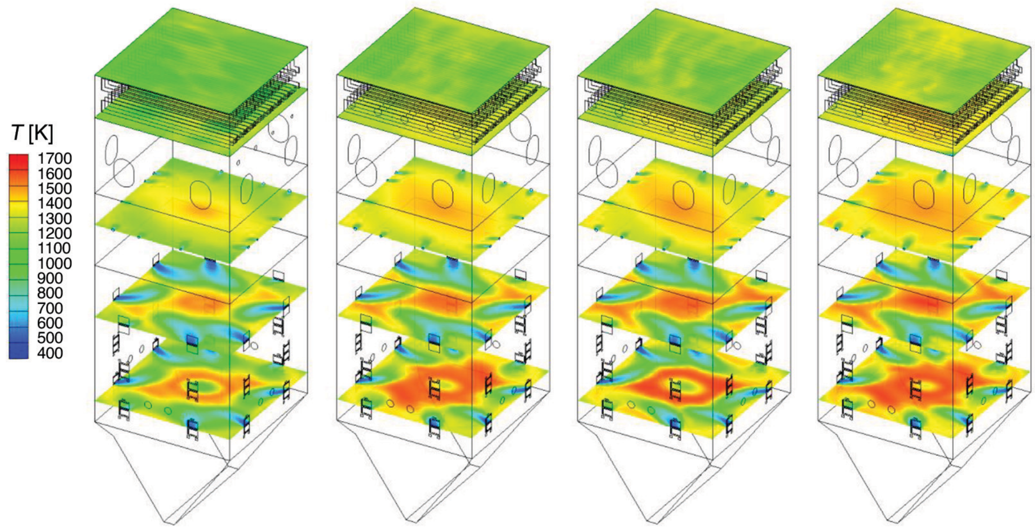

Figure 3. Temperature fields in selected cross-sections of furnace for TC1-TC4

achieve higher flue gas temperatures at the furnace outlet and, thus, larger heat loads in the furnace. By relocating the domain in which post- combustion of unburned particles is obtained, cooling of stream medium, by mixing flue gases with injected finite air flow on second level, is avoided. Such a configuration ensured operation of the furnace with the local value of the excess air ratio at 1.15.

Figures 4 and 5 present oxygen concentration fields in selected cross-sections of the furnace for all considered cases with air staging. Air dosing along the furnace height ensured a significant reduction of zones with high oxygen concentration in the analyzed domain. Such an occurrence is expected due to the less amount of air injected throughout the furnace height. Analyzing central vertical cross-sections, zones in which flue gases are cooled intensively, can be easily noted. In these zones, less oxygen is consumed in the post-combustion process. Only in

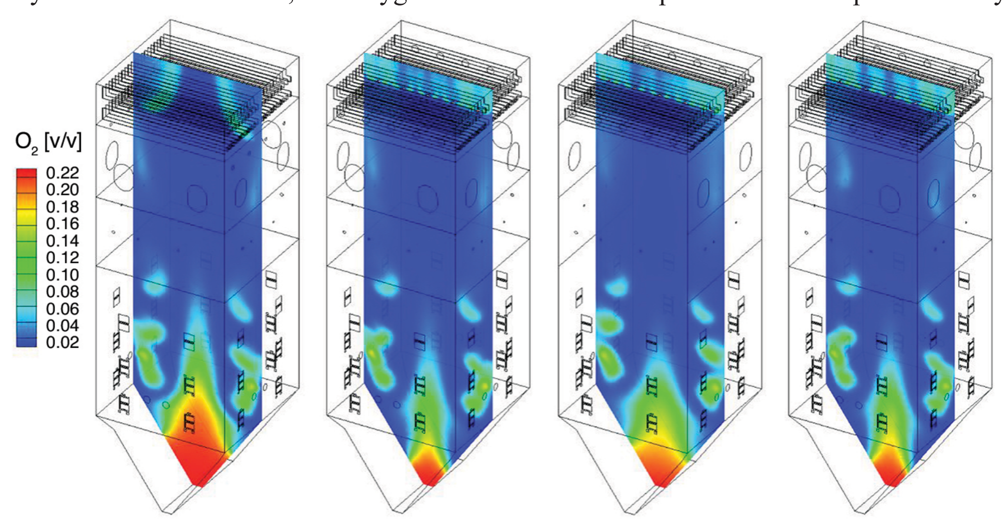

Figure 4. The O_2 concentration fields in the central vertical cross-sections of furnace for TC1-TC4

TC1 configuration, such a sensitive zone is located at the furnace outlet. Unlike to that, intensive cooling of flue gases is obtained where the first stage of the superheater is positioned. In central vertical cross-sections, zones with intensive consumption and concentration of oxygen are observable. In TC2 to TC4 test configurations, such zones are present in a different scope in the area of the second half of the last superheater stage. Considering selected horizontal cross-sections, zones of intensive oxygen concentration and consumption can be clearly noted. Also, by increasing the heat load, free oxygen zones become narrower, which is also supported by a less amount of air injected in TC4 test case.

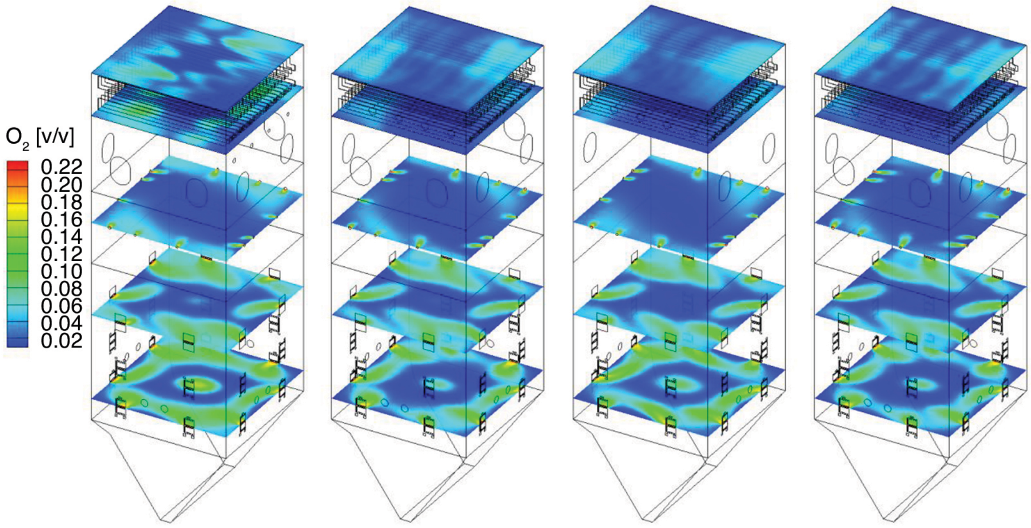

Figure 5. The O_2 concentration fields in selected horizontal cross-sections in furnace for TC1-TC4

In figs. 6 and 7, NO concentration fields in selected furnace cross-sections are shown. Larger portion of NO is generated in burners area and in the vicinity of post-combustion air injection locations. Significant formation of NO occurs near side walls of the furnace and in the

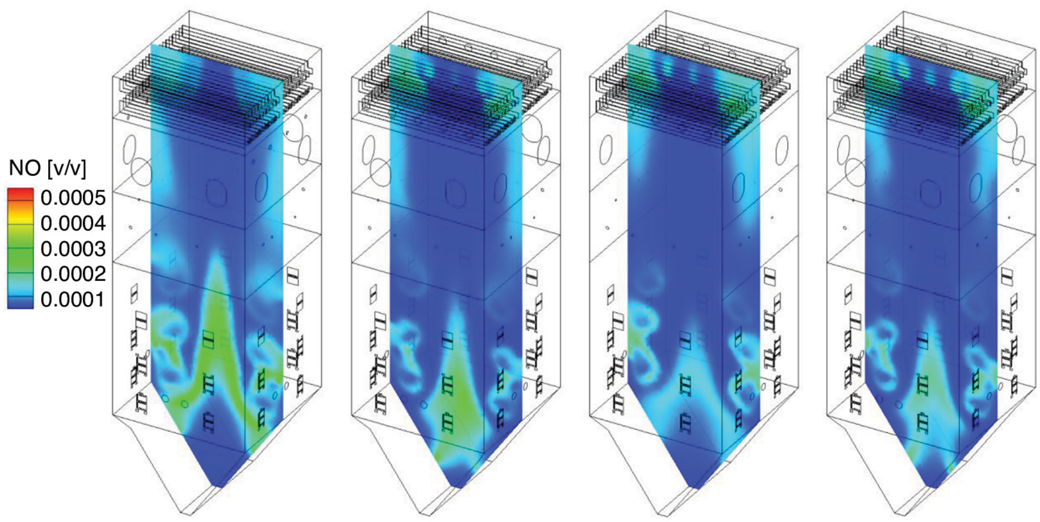

Figure 6. Field of NO concentrations in the central longitudinal section of the furnace for TC1-TC4

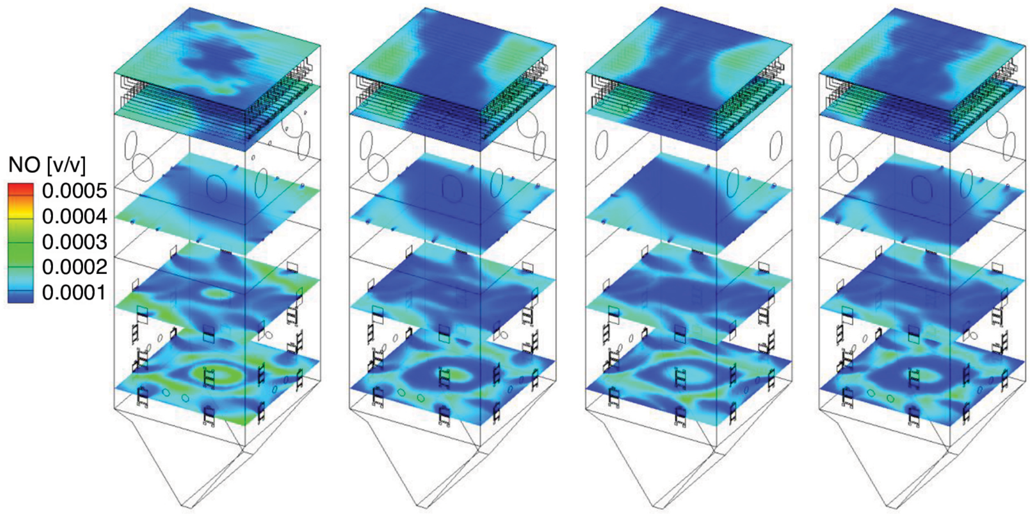

Figure 7. Field of NO concentrations in selected cross-sections of the furnace for TC1-TC4

superheater area, especially if air is injected in the superheater centered at the horizontal cross-section. Thus, it can be concluded that in the area where oxygen is largely consumed in intensive combustion reactions, significant NO formation will be avoided. Accordingly, near the burners zone in TC1 configuration, due to slower combustion process caused by lower heat loads, large portions of NO are formed. Observing central vertical cross-sections of NO concentration, it can be stated that non-uniformity is more intensive when post-combustion is performed above the furnace outlet. Nevertheless, such a configuration provides somewhat smaller concentrations which will always be additionally positively supported by a horizontal introduction of fuel in the furnace through main burners and performing combustion with lower amounts of injected air. It can also be concluded that application of described modifications on the air staging system will lead to a slight attenuation in averaged concentration of NO even if the heat load is being increased.

Air staging application effects on overall steam boiler operation

Table 1 displays selected boundary conditions used in simulations and tab. 2 presents a brief summary of heat balance calculations for all considered test cases. By use of tab. 3, temperature of the heat transmitter and absorber throughout all test cases can be followed. In order to emphasize deviations in respect to designed operational conditions, parallel overview of calculation results for UNR case are also presented.

In all test cases, due to the application of the air staging system, combustion is obtained with a lower value of 1.15 of the excess air ratio. Consequently, more efficient combustion leads to a lower value of the excess air ratio at the boiler outlet, which equals 1.28. Finally, for all test configurations with applied air staging, the efficiency rate of the boiler is higher than the value in the UNR case, which equals 86.26%.

The highest value of 86.77% is achieved in TC1 configuration, where flue gases' temperature at the boiler's outlet is 175 °C. Increase in this temperature to 182 °C in TC4 case leads to a decrease of the efficiency rate to 86.27%. It is important to stress that, in this case, recirculation of cold gases, as one of the measures for reduction of NO_x concentration, is

Table 1. Selected boundary condition

No.	Name		Unit	UNR	R			
					TC1	TC2	TC3	TC4
Mill gaseous mixture								
1.	Mill in operation		-	6/8	6/8	6/8	6/8	6/8
2.	Temperature of mill gases		°C	200	200	200	200	200
3.	Coal dust	Upper vapor burner	kg/s	1.268	1.289	1.152	1.664	1.690
		Lower vapor burner		2.354	1.289	1.152	1.664	1.690
		Upper main burner		2.958	5.148	4.606	4.656	4.760
		Lower main burner		5.493	5.148	4.606	4.656	4.760
4.	Transport fluid	Upper vapor burner	kg/s	12.420	13.676	12.665	12.594	12.133
		Lower vapor burner		11.510	13.676	12.665	12.594	12.133
		Upper main burner		13.972	13.676	12.665	12.594	12.133
		Lower main burner		15.632	13.676	12.665	12.594	12.133
5.	Fractions of gases	CO_2	kg/kg	0.090	0.128	0.110	0.110	0.108
		CO		-	0.003	0.001	0.002	0.003
		SO_2		0.001	0.002	0.001	0.001	0.001
		H_2O		0.194	0.235	0.214	0.217	0.226
		N_2		0.607	0.571	0.589	0.587	0.581
		O_2		0.108	0.061	0.084	0.083	0.080
Air								
6.	Temperature of hot air		°C	299	288	294	295	298
7.	Burner air-flow (in operation / out of operation)	Upper vapor burner – upper stream	kg/s	3.483/1.300	-	-	-	-
		Upper vapor burner – core stream		1.670/0.623	2.978/1.497	2.500/1.332	2.601/1.332	2.454/1.332
		Vapor burners – middle stream		2.059/0.769	-	-	-	-
		Lower vapor burner – core stream		1.670/0.623	2.978/1.497	2.500/1.332	2.601/1.332	2.454/1.332
		Lower vapor burner – lower stream		3.552/1.326	-	-	-	-
		Upper main burner – upper stream		5.572/2.080	2.858/1.436	2.400/1.278	2.496/1.278	2.356/1.278

→

Table 1. (Continous)

No.	Name		Unit	UNR	R			
					TC1	TC2	TC3	TC4
7.	Burner air-flow (in operation / out of operation)	Upper main burner - core stream		1.689/0.631	6.552/3.293	5.500/2.931	5.722/2.931	5.397/2.931
		Upper main burner - lower stream		5.630/2.102	2.502/1.258	2.100/1.118	2.184/1.118	2.060/1.18
		Lower main burner - upper stream		5.684/2.122	1.31/0.659	1.10/0.586	1.144/0.586	1.079/0.586
		Lower main burner - core stream		1.728/0.645	6.652/3.293	5.5/2.931	5.772/2.931	5.397/2.931
		Lower main burner - lower stream		5.746/2.145	4.050/2.036	3.40/1.812	3.538/1.812	3.336/1.812
8.	Air through the furnace hopper	Tertiary air stream		24.185	18.798	20.179	20.399	20.862
		Cold air intake	kg/s	19.650	18.013	19.279	19.562	19.818
9.	Air flow for oil burner cooling		kg/s	3.600	3.600	3.600	3.600	3.600
10.	Flow of OFA 1		kg/s	-	16.784	18.017	18.213	29.803
11.	Flow of OFA 2		kg/s	-	46.995	50.447	50.997	63.331
Wall								
12.	Absorbed amount of heat in third superheater stage	In front of OFA 2	MW	-	83.845	55.676	55.952	59.224
		Behind OFA 2		-		39.117	40.402	46.130
13.	Hot gases re-circulation flow rate		kg/kg	0.203	0.279	0.266	0.261	0.256
14.	Evaporator wall temperature		ºC	365	365	365	365	365
15.	Internal wall emissivity		-	0.55	0.55	0.55	0.55	0.55

Table 2. Heat balance of steam boiler

No.	Name	Mark	Unit	UNR	R			
					TC1	TC2	TC3	TC4
Varied parameters	Main burner inclination	φ_{mb}	º	0	15	15	0	15
	Vapor burner inclination	φ_{vb}	º	0	15	15	15	15
	Excess air at the burner level	λ_{bur}	-	1.22	0.96	0.96	0.96	0.90
	Excess air at the OFA 1 level	$\lambda_{of\,a1}$	-	1.22	1.01	1.01	1.01	0.98
	Excess air at the OFA 2 level	$\lambda_{of\,a2}$	-	1.22	1.15	1.15	1.15	1.15

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Table 2. (Continous)

No.	Name	Mark	Unit	UNR	R			
					TC1	TC2	TC3	TC4
Varied parameters	Excess air at the furnace outlet	λ_{fo}	-	1.22	1.15	1.01	1.01	0.98
	Excess air at the third superheater outlet	λ_1	-	1.22	1.15	1.15	1.15	1.15
	Increase of excess air in furnace	$\Delta\lambda_f$	-	0.052	0.05	0.05	0.05	0.05
	Increase of excess air in mill	$\Delta\lambda_m$	-	0.128	0.12	0.12	0.12	0.12
	Total increase of excess air in furnace and mill	$\Delta\lambda$	-	0.18	0.17	0.17	0.17	0.17
	Recirculation rate of cold gases	r_2	-	0.061	0.077	0.077	0.077	0.077
	Pulverized coal sieve residue	R_{1000}	%	10	4	4	4	4
		R_{90}	%	63	55	55	55	55
1.	Excess air at the boiler outlet	λ_{out}	–	1.32	1.28	1.28	1.28	1.28
2.	Temperature of outlet gases	t_{out}	°C	179	175	179	180	182
3.	Waste gas loss	q_2	%	11.37	10.86	11.14	11.19	11.36
4.	Loss due to unburned gases	q_3	%	0.00	0.00	0.00	0.00	0.00
5.	Loss due to incomplete mechanical combustion	q_4	%	2.12	2.12	2.12	2.12	2.12
6.	Radiation loss	q_5	%	0.19	0.19	0.19	0.19	0.19
7.	Loss due to slag heat	q_6	%	0.06	0.06	0.06	0.06	0.06
8.	Boiler efficiency	η_{sb}	%	86.26	86.77	86.49	86.44	86.27
9.	Amount of heat used in steam boiler	Q_{sb}	MW	840.881	751.084	803.645	811.951	828.769
10.	Fuel consumption	B	kg/s	114.704	101.892	109.377	110.570	113.079

Table 3. Selected results of the thermal calculations

No.	Name	Mark	Unit	UNR	R			
					TC1	TC2	TC3	TC4
Heat absorber (water and steam)								
1.	Boiler load	D	t/h	1060	1060	1060	1060	1060
2.	Injection in desuperheater No. 1	D_{H1}	kg/s	15.300	0.000	0.000	5.000	12.000
3.	Injection in desuperheater No. 2	D_{H2}	kg/s	8.584	0.188	0.650	0.113	13.340
4.	Injection in desuperheater No. 3	D_{Hr}	kg/s	14.377	0.159	2.324	4.074	10.064
5.	Temperature of steam on the third superheater entrance	t_{sh3i}	°C	466	427	449	451	444

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Table 3. (Continous)

<table>
<tr><th rowspan="2">No.</th><th rowspan="2" colspan="2">Name</th><th rowspan="2">Mark</th><th rowspan="2">Unit</th><th rowspan="2">UNR</th><th colspan="4">R</th></tr>
<tr><th>TC1</th><th>TC2</th><th>TC3</th><th>TC4</th></tr>
<tr><td>7.</td><td colspan="2">Temperature of steam on the second reheater outlet</td><td>t_{sh2io}</td><td>°C</td><td>540</td><td>518</td><td>540</td><td>540</td><td>540</td></tr>
<tr><td>8.</td><td colspan="2">Pressure of superheated steam</td><td>p_s</td><td>bar</td><td>180.0</td><td>180.0</td><td>180.0</td><td>180.0</td><td>180.0</td></tr>
<tr><td>9.</td><td colspan="2">Pressure of reheated steam</td><td>p_{rs}</td><td>bar</td><td>43.7</td><td>43.7</td><td>43.7</td><td>43.7</td><td>43.7</td></tr>
<tr><td colspan="10">Heat absorber (air)</td></tr>
<tr><td>10.</td><td colspan="2">Temperature of hot air</td><td>t_{ha}</td><td>°C</td><td>299</td><td>288</td><td>294</td><td>295</td><td>298</td></tr>
<tr><td colspan="10">Heat transmitter (flue gases)</td></tr>
<tr><td>11.</td><td colspan="2">Temperature of flue gases on the furnace outlet</td><td>t_{fo}</td><td>°C</td><td>1091</td><td>952</td><td>1054</td><td>1063</td><td>1114</td></tr>
<tr><td>12.</td><td colspan="2">Temperature of flue gases behind the third superheater</td><td>t_1</td><td>°C</td><td>996</td><td>842</td><td>900</td><td>915</td><td>969</td></tr>
<tr><td>13.</td><td colspan="2">Temperature of outlet gases</td><td>t_{out}</td><td>°C</td><td>179</td><td>175</td><td>179</td><td>180</td><td>182</td></tr>
<tr><td colspan="10">Absorbed amount of heat</td></tr>
<tr><td>14.</td><td colspan="2">Economizer</td><td>Q_{eco}</td><td>kJ/kg</td><td>941.0</td><td>761.7</td><td>819.3</td><td>831.4</td><td>869.1</td></tr>
<tr><td rowspan="2">15.</td><td rowspan="2">Evaporator</td><td>Furnace</td><td rowspan="2">Q_e</td><td rowspan="2">kJ/kg</td><td>1671.1</td><td>2507.3</td><td>2142.5</td><td>2050.7</td><td>1683.4</td></tr>
<tr><td>Additional heating surfaces</td><td>495.3</td><td>406.2</td><td>457.0</td><td>466.9</td><td>512.9</td></tr>
<tr><td>16.</td><td colspan="2">First superheater stage</td><td>Q_{sh1}</td><td>kJ/kg</td><td>404.9</td><td>561.4</td><td>479.3</td><td>458.7</td><td>376.2</td></tr>
<tr><td>17.</td><td colspan="2">First part of second superheater stage</td><td>Q_{sh21}</td><td>kJ/kg</td><td rowspan="2">1887.6</td><td>636.5</td><td>725.7</td><td>745.1</td><td>819.4</td></tr>
<tr><td>18.</td><td colspan="2">Second part of second superheater stage</td><td>Q_{sh22}</td><td>kJ/kg</td><td>738.2</td><td>829.9</td><td>860.0</td><td>953.8</td></tr>
<tr><td>19.</td><td colspan="2">Third (output) superheater stage</td><td>Q_{sh3}</td><td>kJ/kg</td><td>617.9</td><td>744.8</td><td>778.2</td><td>781.7</td><td>834.2</td></tr>
<tr><td>20.</td><td colspan="2">First reheater stage</td><td>Q_{rh1}</td><td>kJ/kg</td><td>868.2</td><td>669.9</td><td>735.1</td><td>748.8</td><td>805.4</td></tr>
<tr><td>21.</td><td colspan="2">Second (output) reheater stage</td><td>Q_{rh2}</td><td>kJ/kg</td><td>667.4</td><td>505.0</td><td>539.8</td><td>559.3</td><td>633.1</td></tr>
<tr><td>22.</td><td colspan="2">Air preheater</td><td>Q_{aph}</td><td>kJ/kg</td><td>901.9</td><td>783.7</td><td>803.1</td><td>806.5</td><td>819.2</td></tr>
</table>

enlarged from 6.1 to 7.7%. Thus, without enlarging the re-circulation rate of cold gases, presented results might be even better.

It is important to stress that operation of the boiler with 840.881 MW and fuel consumption of 114.704 kg/s is obtained with significant dosing of water in desuperheaters for maintaining the temperature of the superheated and reheated steam. Mass-flow of injected water in the superheated steam line equals 23.884 kg/s, while in the reheated steam line it equals 14.337 kg/s. In this test case, the boiler is capable of achieving and maintaining the designed temperature of the superheated and reheated steam, which equals 540 °C.

Boiler operation in TC1 provides a heat output of only 751.084 MW with the fuel consumption of 101.892 kg/s. In such working conditions, the boiler generates superheated steam with 498 °C temperature and reheated steam with 518 °C. Apparently, the complete regulation area in these operational conditions is lost. Such results are a consequence of the intensified heat transfer within the furnace achieved with applied air staging. In comparison with UNR case, specific heat absorbed in the furnace is higher by 836.2 kJ/kg and equals 2507.3 kJ/kg. Such an increase in the specific amount of heat absorbed can be explained by obtaining the heat transfer in conditions of high temperature potential in the combustion zone, due to the reduced amount of air injected. This effect is made clearly notable by injecting a finite amount of air at the furnace outlet zone. In this area, post-combustion of only a small number of unburned particles is provided, while flue gases' temperature is significantly decreased locally. Thus, this temperature is changed from 1091 °C in UNR case to 952 °C. Consequently, all other heating surfaces within the boiler, designed to operate by the conventional combustion scheme, absorb a smaller amount of heat, which finally results in the reduction of the designed boiler power.

Possibility to avoid such a negative effect of air staging implementation was considered throughout TC2 to TC4 cases. By replacing OFA 2 in TC2, unfavorable cooling of flue gases is postponed and moved from the critical outlet furnace zone. Cooling of flue gases due to the injection of a finite amount of air along with the post combustion process is placed in the middle horizontal cross-section of the last stage of the superheater. Although temperature decrease of the heat transmitter is obtained (in comparison with UNR case of 37 °C), reduction is significantly smaller while the boiler power is enlarged and equals 803.645 MW. Fuel consumption in these operational conditions was 109.377 kg/s. Redistribution of the specific absorbed amount of heat also happened. In the furnace, 2142 kJ/kg was received in the furnace evaporator, while 778.2 kJ/kg of the heat was transferred in the outlet stage of the superheater. It can be concluded that the decrease in the specific absorbed amount of heat provided an increase in the heat absorbed in the outlet stage of the superheater, which was ensured by a higher temperature of flue gases at the furnace outlet. Finally, with the application of TC2 combustion scheme, temperature of the superheated steam was partially regained to 536 °C, while the designed temperature of the reheated steam was completely achieved. Yet, a considerable increase of the heat absorbed in the furnace resulted in a significant reduction of the regulation area in the reheated steam line with the steam mass flow of 2.324 kg/s.

In TC3 test case, main burners axes were additionally rotated towards the furnace outlet. Such a rotation postponed the beginning of combustion and the heat transfer processes. Thus, the temperature of flue gases at the furnace outlet increased, as expected, and equaled 1063 °C. Therefore, the specific amount of heat absorbed in the furnace is additionally decreased to 2050.7 kJ/kg, while in the outlet stage of the superheater it is slightly increased to 781.7 kJ/kg. Also, the boiler power was increased to 811.951 MW with the coal consumption of 110.570 kg/s. In such settings, the designed temperatures of the superheated and the reheated steam was achieved, while the regulation area was preserved in a reduced scope. Mass flow of injected water was 5.113 kg/s in the superheated line and 4.047 kg/s in the reheated line.

After confirming the capability to achieve the designed states of the superheated and reheated steam, finally the TC4 case was considered. In this test case, the possibility of additional slowing down of the combustion process was considered in order to further negatively accelerate the heat transfer process. Retaining all other settings, the redistribution of air injection along the furnace height was performed. Amount of air injected through OFA 2 was increased, while the air injected in the furnace is reduced for the same amount. Such a modification provided an increase of the boiler power to 828.769 MW with 113.079 kg/s fuel consumed. The gained power boiler growth was caused by the reduction of the specific absorbed amount of heat to the designed level, which equals 1683.4 kJ/kg. Even in this case, such an occurrence was followed by the growth of the furnace outlet flue gas temperature to 1114 °C and the increase of the specific amount of heat absorbed in the superheater stage, which equals 834 kJ/kg. Designed outlet temperatures of the superheated and reheated steam were also achieved, while the mass-flow of water injected in desuperheaters was 25.360 kg/s in the superheated steam line and 10.064 kg/s in the reheated steam line.

Considering calculation results of the main process parameters, it can be concluded that the furnace and the semi-radiative superheater always receive larger portions of heat in any of considered air staging test cases. Consequently, the temperature of the flue gas, after the third superheater, is always reduced in comparison with the UNR case. All considered cases with air staging met the requirements regarding the level of unburned fuel at the boiler outlet. Numerical calculations also revealed that there is no significant concentration of carbon monoxide at the outlet of the domain after the superheater.

Table 4 presents the boiler ecological performance parameters. Concentrations of NO_x is, in any case with applied primary measure, lower in comparison to the designed value in the UNR case, which is 485 mg/Nm^3. For instance, with TC1 configuration the concentration equals 225 mg/Nm^3 and is reduced in all other considered cases, regardless of the applied boiler heat load. Locating OFA 2 in higher zones and injecting a smaller amount of air flow in the furnace is favorable for achieving even lower concentrations of nitrogen oxides in flue gases at the boiler outlet. According to that, the lowest concentration of NO_x is achieved in TC4 and equals 195 mg/Nm^3, along with the final excess air ratio of 1.15.

Table 4. Selected results of the boiler calculation system

No.	Name	Mark	Unit	UNR	R			
					TC1	TC2	TC3	TC4
1.	Concentration of oxygen in wet flue gases	c_1	%vv^{-1}	3.46	2.76	2.58	2.52	2.69
2.	Concentration of water vapor in wet flue gases	c_2	%vv^{-1}	20.06	21.28	21.43	21.59	21.50
3.	Concentration of oxygen in dry flue gases	c_3	%vv^{-1}	4.30	3.51	3.28	3.22	3.43
4.	Concentration of CO at reference conditions	(CO)*r*	mgNm^{-3}	–	32	0	0	0
5.	Concentration of NO_x at reference conditions	$(NO_x)r$	mgNm^{-3}	485	225	204	201	195

Conclusions

This study presents the results of performed calculations of NO_x concentration before and after the application of the air staging system on the existing power steam boiler. New combustion scheme was implemented during 2015 on the power steam boiler within unit 1 of TPP Kostolac B. Measurements performed on site showed that applied modifications led to a permanent loss of the steam boiler power. This study was performed in order to define the cause of such an occurrence and to consider the possibility for regaining the designed steam parameters along with keeping the level of NO_x concentration in prescribed limits. Four test cases, with the change of air distribution throughout the furnace height and the slope of main burner axes, were considered. In all considered configurations, same fuel with LHV of 8373.6 kJ/kg was utilized. Constant mass-flow of produced steam was also retained throughout all calculation procedures (1060 per hours).

In this paper, an overall review of gained results of all considered cases along with parameters of the boiler before the reconstruction, has been shown. Tables presented emphasized that the flue gases' temperature at the furnace outlet in the designed combustion configuration is

1091 °C and the excess air ratio is 1.22. This value of flue gases' temperature ensures the designed parameters of steam at the superheater and the reheater line outlet at the level of 540 °C. Also, designed combustion configuration provides a considerably large regulation area. Mass-flow of injected water in desuperheaters was 23.884 kg/s for the superheated steam line and 14.377 kg/s for the reheated steam line. Although the efficiency rate of 86.26 % and all steam parameters were achieved, the concentration of NO_x was unacceptable at the rate of 485 mg/Nm^3.

Research also showed that the application of the air staging system provides a larger specific amount of absorbed heat. This effect is obtained due to higher values of the local temperature field in zones with a lower concentration of injected air. Additionally, it has been shown that the intensity of the heat process can be influenced by the sub-stoichiometric rate achieved in the furnace. Analysis also revealed that the location of OFA 2 is of great importance for achieving the designed steam parameters. This position determines the zone in which the post-combustion takes place and the final cooling of flue gases by injected air is obtained.

Due to the specified position of OFA 2, the lowest value of flue gas temperature is achieved in TC1 configuration, which equals 952 °C. Such a state of the heat transmitter provoked an impossibility to transfer enough heat in the last stage of the superheater to obtain the desired temperature of the superheated steam at the boiler outlet. Essentially, TC1 configuration ensured the redistribution of the heat received by all heating surfaces so that larger portions of the heat are transferred in the evaporator. Consequently, achieved temperatures of the superheated and reheated steam were 498 °C and 518 °C, respectively. On the contrary, the efficiency rate of the steam boiler was 86.77%, while the concentration of NO_x exceeded prescribed limitations and equaled 225 mg/Nm^3.

By raising OFA 2 in TC2 case, the temperature drop was significantly reduced and the outlet flue gas temperature equaled 1054 °C. Temperature of the superheated steam of 536 °C was partially regained, while parameters of the reheated steam were completely recovered. Although this configuration eliminated some negative effects occurred in TC1 configuration, the boiler power was not fully regained, the efficiency rate was at 86.49% followed by 204 mg/Nm^3 concentration of NO_x in flue gases.

Additional placing main burners axes in the horizontal plane in TC3 configuration, even higher temperatures of flue gases at the furnace outlet are achieved and equal 1063°C. In this case, designed temperatures of the superheated and the reheated steam are obtained, while the regulation area is significantly reduced. Water-flow in desuperheaters equals 5.113 kg/s for the superheaters line and 4.074 kg/s for the reheaters line. The efficiency rate in such settings equals 86.44%. Concentration of NO_x almost reaches the prescribed values and equals 201 mg/Nm^3.

Finally, after the redistribution of injected air between main burners and OFA levels in TC4 case, combustion reactions are additionally negatively accelerated. As a result of this modification, temperature of flue gases at the furnace outlet reaches 1114 °C. Desired parameters of the steam are again achieved with a difference that, in this case, a considerably higher water flow injected in desuperheaters is required. Mass-flows of water injected in the superheaters and the reheaters line are 25.34 kg/s and 10.064 kg/s, respectively. Thus, with this modification, the regulation area is significantly enlarged. In these operational conditions, the efficiency rate is retained at the designed level and equals 86.27%. Additionally, NO_x concentration in the furnace outlet is reduced and equals 195 mg/Nm^3. Summarizing all occurred effects, it can be concluded that this modification ensures optimal working conditions regarding all important criteria.

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