POSSIBILITIES OF STEAM BOILER PROCESS OPTIMIZATION IN THE TPP UGLJEVIK

by

Goran M. STUPAR[a*], Dragan R. TUCAKOVIĆ[a], Ognjen S. STAMENKOVIĆ[a], Luka PETROVIĆ[b], Borivoje VUJIČIĆ[b], Žarko NOVAKOVIĆ[b], and Željko MILANOVIĆ[b]

[a] Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia
[b] Electric Power Industry of Republika Srpska, Trebinje, Republic of Srpska, Bosnia and Hercegovina

Original scientific paper
https://doi.org/10.2298/TSCI2301133S

The paper presents a technical solution for modernization with the aim of increasing the efficiency of the steam boiler of TPP Ugljevik, which implies the reorganization of the combustion system. More efficient operation of the furnace can be achieved by replacing the existing burners, reducing the number of burner levels as well as the organization of tangential combustion. The flame formed in the shape of a tube around the two central combustion vortices provides a larger amount of heat transferred to the combustion furnace, less fouling of its screen walls and thus a lower average temperature of the combustion products at its outlet. As the chosen reorganization affects the increase of the temperature of the superheated steam and the decrease of the temperature of the reheated steam, it has been proposed to reduce the area of the semi-irradiated superheater and increase the area of the second reheater. Taking into consideration that the reorganization of the combustion system may lead to the change of the thermal load of the evaporator located in the furnace, the paper presents the work of the steam boiler operation under new operating conditions. Used calculation system enables reliable prediction of operating characteristics of the steam boiler in new operating conditions of combustion, and its application helps assess the quality of the boiler in terms of how effective, efficient, safe and environmentally friendly its operating mode is. In this way, it is possible to form a comprehensive description of the operating mode of the steam boiler.

Key words: *steam boiler, furnace, calculation system, efficiency*

Introduction

A steam unit of 300 MW power has been in use in TPP Ugljevik since 1985, with more than 200000 working hours in production. The steam unit has reached the end of its service life, and has, because of the obsolescence of equipment and frequent use of coal with increased propensity to slagging and fouling, been operating with less power, increased number of unplanned outages and frequent downtime due to cleaning of deposits on heating surfaces.

In order to check the operation of the steam unit, identify the main problems in its operation and set guidelines for increasing its availability, power and efficiency – it is necessary to define mathematical models of complex thermal and stream processes [1, 2] which,

* Corresponding author, e-mail: gstupar@mas.bg.ac.rs

with the implementation of a number of control calculations, enable the analysis of the existing state of the plant [3] and give proposals of measures for improvement of its operation as a whole. The use and benefits of such a complex model is shown through papers [4-6].

In order to test the possibility of applying measures of reorganization of the combustion process as well as the analysis of their effects on the steam boiler operation, a modeling of the lignite combustion process in the steam boiler furnace of TPP Ugljevik has been performed. A comprehensive description of the process in the furnace of the energy steam boiler for coal combustion is defined by a mathematical model of radiated reactive two-phase turbulent flow together with a submodel of fuel and thermal nitrogen oxides formation [7-9]. Such a complex mathematical model is connected with thermal calculation procedures into a unique calculation system for the analysis of steam boiler operation. The defined system enables calculations with the change of influential parameters in the widest limits, which was applied for calculations of steam boiler operating regimes for the design combustion system, as well as the reorganized combustion system, after the proposed modernization.

The changes in the operation of the considered steam boiler after the introduced measures are presented by the relevant results of the calculation system in case of change of its load for thermal power fuel currently used in the power plant and in variants of greater and less tendency to slag and fouling heating surfaces.

The performed calculations, previously verified and validated by measurements [10] at the plant in question shown [11-13], showed problems in its operation, based on which, for coal to be used in the next period, additional measures and reconstructions of the boiler plant were proposed in order to increase the current steam production.

The steam boiler of TPP Ugljevik, shown in fig. 1, consists of a water heater, an evaporator located in the furnace, three stages of steam superheater and two stages of steam reheater. The regulation of the temperature of fresh and reheated steam is done by biflux and the desuperheaters water injection placed between the heating surfaces. The boiler is equipped with eight individual plants for the preparation of coal powder, designed as modified plants with direct blowing and drying by a closed process. Each coal powder preparation plant has one jet burner which is divided in height into three levels, which are inclined towards the furnace funnel at an angle of 15°. In the furnace of the boiler, of rectangular cross-section, four burners were placed on both side walls. The two central jet burners are placed opposite, and the other two end ones are slightly turned, by 13° 30' in the horizontal plane, towards the central axis of the furnace.

Through multi-level jet burners for coal, air mixture and secondary air are introduced into the furnace of the steam boiler. In the burner zone, their intensive mixing, burning and combustion of coal particles is performed. In the combustion process, high-temperature combustion products (heat transmitter) are formed, which further flow through the boiler, transferring energy to the water-steam flow (heat receiver) by means of heating surfaces. The products of combustion of coal particles formed in the zone of the burner flow vertically upwards, transferring the amount of heat by radiation to the membrane pipes that shield the walls of the furnace.

Due to the 'T' shape of the gas path of the steam boiler in question, the combustion products leave the furnace by dividing into two parts and entering two symmetrically placed horizontal gas intermediate channels in which two semi-irradiated fresh steam superheaters are installed. The walls and ceiling of the horizontal gas intermediate channel are shielded with membrane pipes which, along the heat receiver, represent a continuation of the screen pipes of the middle and upper radiation part of the furnace and form additional heating surfaces in this

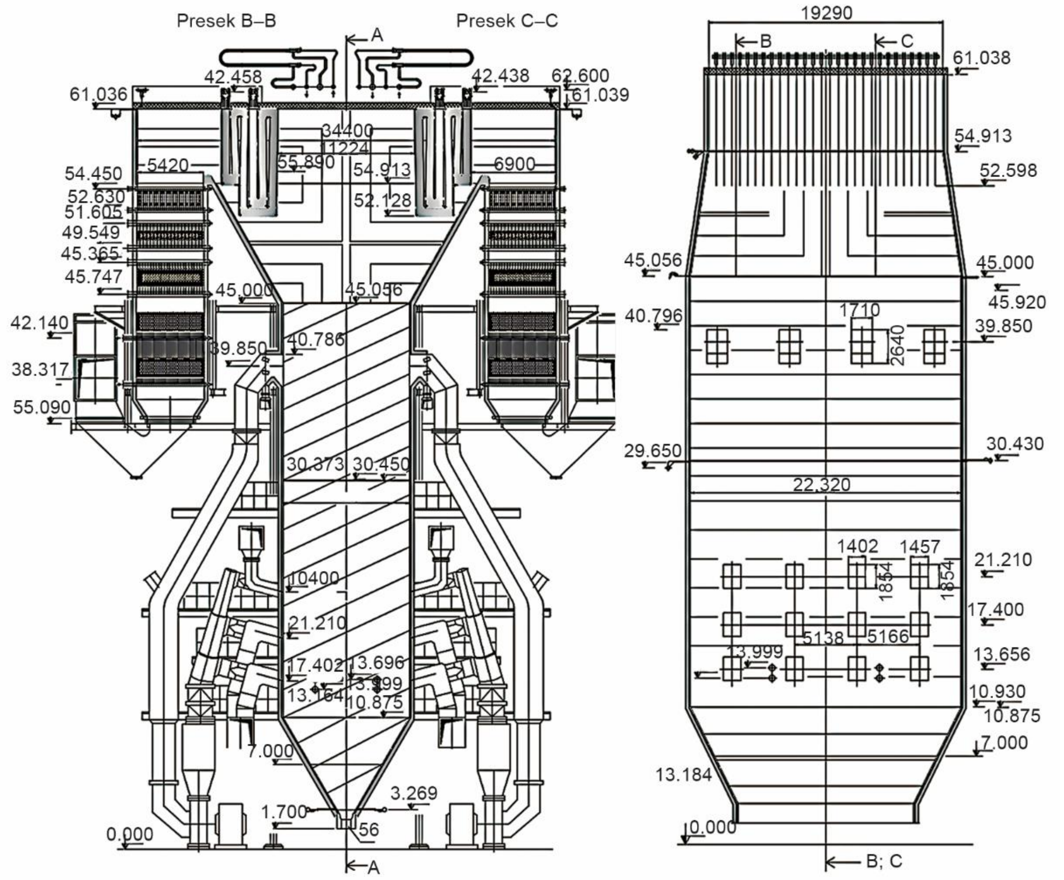

Figure 1. Steam boiler in TPP Ugljevik

The design characteristics of the steam boiler, for guaranteed coal with a lower heating value of 10467 kJ/kg, are:
- Unit power, P = 300 MW
- Main steam mass flow rate, D = 1000 t/h
- Main steam pressure, p_s = 25.0 MPa
- Main steam temperature, t_s = 545 ^{o}C
- Reheated steam mass flow rate, D_{rs} = 800 t/h
- Reheated steam pressure, p_{rs} = 3.84 MPa
- Reheated steam temperature, t_{rs} = 545 ^{o}C
- Steam pressure at the reheated inlet, p_r = 4.19 MPa
- Steam temperature at the reheated inlet, t_r = 306 ^{o}C
- Feed water pressure p_{nv} = 30.8 MPa
- Feed water temperature t_{nv} = 275 ^{o}C
- Boiler efficiency η_k = 86 ±0.5**%**

part of the gas tract. At the end of the horizontal gas intermediate channel, both streams of combustion products turn downwards and enter two vertical convective gas channels symmetrically placed in relation to the vertical axis of the boiler. Convective (outlet) superheater 3, convective (outlet) reheater 2, convective reheater 1 and two packages of water heaters were placed in order along the combustion products in these gas channels. These heating surfaces are placed in both gas channels symmetrically in relation to the vertical axis of the furnace. Vertical convective gas ducts are not shielded by pipes of additional heating surfaces.

After the transferred amount of heat in the vertical convective gas ducts, the combustion products reach the ash funnels, turn and enter two horizontal tin flue ducts, placed directly next to the vertical convective gas ducts of the boiler. After that, the flue gases are divided from two gas channels and introduced into three columns of a tubular air preheater of cascade type. In the air preheater, the combustion products reached the final outlet temperature and, after dedusting, released into the atmosphere. In the air preheater, the combustion products reached the final outlet temperature and, after dedusting, released into the atmosphere.

Analysis of the steam boiler calculation system

Steam boiler operating mode calculation system

In order to reach variant solutions for the organization of processes in the furnace and the resulting effects on the operation of the steam boiler, modelling of coupled complex processes in the power steam boiler of TPP Ugljevik was performed for working conditions with new arrangement of burners. For the purpose of predicting the operation of the complex boiler plant, regardless of the concept of combustion applied in its furnace, an algorithm has been defined for connecting integral calculations of the boiler and numerical calculations of the element whose work is analysed in more detail. The modelling of these processes was performed using a software system that includes a differential and integral mathematical model with their interaction. This system enables a broader overview of all relevant states of currents involved in the flow, combustion and heat transfer in the furnace of the steam boiler. This model was verified where the results of the integral, zonal and numerical model of the processes in furnaces were confirmed. It has been shown that different organizations of the combustion process can be tested with this model. The verification was carried out by the design integral and zonal thermal calculation of the boiler, while the validation was carried out on the basis of the measured process data parameters. Bold values shown in tabs. 2 and 3 are used for model validation. This system tool served as the basis for the presented research. The applied mathematical model describes the formation and radiant reactive multiphase turbulent flow and provides a detailed insight into such complex and coupled processes that take place simultaneously in the combustion zones of the steam boiler furnace. The mathematical submodel of formation and destruction of fuel and thermal nitrogen oxides, NO_x, is also included in the overall model. The defined system enables calculations with changes of influential parameters in the widest limits (coal quality, heating surface fouling rate, quantities and velocity of air mixture and air, combustion products recirculation rate, orientation of burners). In the described way, the system enables monitoring of the operation of a complex energy system and testing a measures that affect its operation which is shown in the papers [6, 12, 13]. Applying the mentioned system, the appropriate calculations of the existing furnace with the design conventional combustion system within TPP Ugljevik were performed and the system of reorganization of the process in the furnace was proposed.

By analysing the obtained results, it is possible to give guidelines for improving the process in order to increase its power, efficiency, reliability, and environmentally acceptable way of operating. The described procedure was applied in the testing of the new combustion organization in TPP Ugljevik, which includes burners of new construction and tangential organization of superstoichiometric combustion in the furnace, so the described procedure was used to select burner geometry, as well as their place and angle [14].

Boiler calculation system results

Based on the given models, the calculation of work in design conditions (unreconstructed – UNR) was performed, as well as with the proposed reorganized combustion system, when two same directions flames are formed in the furnace around central vortices, optimal in terms of temperature field symmetry and absence of particularly unfavorable high local temperature zones near the screen walls, as shown in test cases TC1-TC4. For this selected system, CFD calculations of steam boiler operation were performed for a unit power of 260 MW, with turned off and on high pressure feed water heaters (HPH) and 300 MW with turned on high pressure feed water heaters, and each of the tested operating modes was tested using coal more or less prone to fouling, the composition of which is given in tab. 1 and which is close to the guaranteed. Control thermal calculations were performed for the existing steam boiler, in order to determine the temperatures of heat transmitters and receivers at the inlet and outlet of heating surfaces, in accordance with the heat balance shown in tab. 2. Thermal calculations, whose selected results are shown in tab. 3, were performed according to the normative method [15], while the level of fouling and thermal efficiency of individual heating surfaces were harmonized with the current operation of the boiler. When calculating the process in the furnace, the redistribution of coal particles, transport fluid and heated air by levels of burners was adopted on the basis of measurements after the reconstruction of the air mixture separator in 2020, which means that the air mixture is divided in mass ratio 51:30:19 and that the excess air 1.24 for the unit power of 260 MW, which can be achieved with the current quality of coal and the design combustion.

Table 1. Coal composition – lignite Ugljevik *LHV* = 10341 kJ/kg

Raw coal			Coal particles at separator outlet			Dry ash free			Proximate analysis		
C^r	[%]	29.13	C^p	[%]	39.79	C^{DAF}	[%]	70.81	$V_{olatile}$	[%]	40.12
H^r	[%]	2.05	H^p	[%]	2.80	H^{DAF}	[%]	4.98	C_{fix}	[%]	16.08
O^r	[%]	7.22	O^p	[%]	9.86	O^{DAF}	[%]	17.55	A	[%]	37.10
N^r	[%]	0.81	N^p	[%]	1.11	N^{DAF}	[%]	1.97	W	[%]	6.70
S_g^r	[%]	1.93	S_g^p	[%]	2.64	S_g^{DAF}	[%]	4.69			
A^r	[%]	27.16	A^p	[%]	37.10						
W^r	[%]	31.70	W^p	[%]	6.70						

Table 2. Boiler heat balance extracts for the existing and reorganized combustion system

No.	Name	Mark	Unit	Unit power [MW]					
				260				300	
				Without HPH		With HPH			
				UNR*	**UNR****	TC1*	TC2**	TC3*	TC4**
1.	Lower heating values of raw coal	*LHV*	[kJkg^{-1}]	**10341**	10341	10341	10341	10341	10341
2.	Excess air at the furnace outlet	λ_{fo}	[–]	**1.240**	1.240	1.240	1.240	1.200	1.200
3.	Increase of excess air in furnace	$\Delta\lambda_f$	[–]	0.150	0.150	0.110	0.110	0.080	0.080
4.	Increase of excess air in mill	$\Delta\lambda_m$	[–]	0.258	0.258	0.140	0.140	0.120	0.120
5.	Air leakage from the air preheater	$\Delta\lambda_{ah}$	[–]	0.216	0.216	0.072	0.074	0.054	0.054
6.	Excess air at the boiler outlet	λ_{out}	[–]	**1.686**	1.686	1.452	1.452	1.374	1.374
7.	Temperature of outlet gases	t_{out}	[ºC]	**223**	208	185	178	187	179
8.	Waste gas loss	q_2	[%]	15.44	14.28	11.22	10.73	10.34	10.34
9.	Loss due to unburned gases	q_3	[%]	0	0	0	0	0	0
10.	Loss due to incomplete mechanical combustion	q_4	[%]	2.08	2.08	2.08	2.08	1.80	1.80
11.	Radiation loss	q_5	[%]	0.14	0.14	0.14	0.14	0.12	0.12
12.	Loss due to slag heat	q_6	[%]	0.07	0.07	0.07	0.07	0.07	0.07
13.	Boiler efficiency	η_{sb}	[%]	82.27	83.43	86.49	86.98	87.16	87.67
14.	Boiler load	*D*	[kJs^{-1}]	**207.50**	207.50	214.93	214.93	251.50	251.50
15.	Temperature of superheated steam	t_s	[ºC]	**545**	545	545	545	545	545
16.	Pressure of superheated steam	p_s	[bar]	**243.53**	243.53	244.12	244.12	247.36	247.36
17.	Feed water temperature	t_{fw}	[°C]	**164.3**	164.3	266.3	266.3	270.5	270.5
18.	Feed water pressure	p_{fw}	[bar]	**274.21**	274.21	275.97	275.97	290.96	290.96
19.	Production of reheated steam	D_r	[kJs^{-1}]	**203.50**	203.50	191.65	191.65	224.95	224.95
20.	Temperature of reheated steam	t_{rs}	[ºC]	**545**	538	545	545	545	545
21.	Pressure of reheated steam	p_{rs}	[bar]	**34.80**	34.80	33.00	33.00	38.28	38.28
22.	Temperature of steam for reheating	t_r	[ºC]	**304.4**	304.4	285.4	285.4	298.7	298.7
23.	Pressure of steam for reheating	p_r	[bar]	**37.40**	37.40	34.52	34.52	40.38	40.38
24.	Amount of heat transferred to the turbine economizer (TuE)	Q_{TUE}	[MW]	–	–	35.1	35.1	41.1	41.1
25.	Amount of heat used in steam boiler	Q_{sb}	[MW]	659.62	656.41	618.24	618.24	712.94	712.94
26.	Fuel consumption	*B*	[kJs^{-1}]	76.434	75.005	68.568	68.186	78.468	78.010

* Boiler operation with coal of greater tendency to slag.
** Boiler operation with coal of less tendency to slag

Table 3. Thermal calculations extracts for the existing and reorganized combustion system

No.	Name	Mark	Unit	Unit power [MW]					
				260				300	
				Without HPH		With HPH			
				UNR*	**UNR****	TC1*	TC2**	TC3*	TC4**
Heat transmitter (flue gases)									
1.	Temperature of flue gases on the furnace outlet	t''_f	[°C]	**1044**	968	919	886	957	922
2.	Temperature of flue gases behind the semi-irradiated superheater	t_1	[°C]	876	815	821	791	860	828
3.	Temperature of flue gases in front of convective superheater	t_2	[°C]	**852**	791	799	771	836	806
4.	Temperature of flue gases in front of the second superheater stage	t_3	[°C]	778	723	734	703	763	729
5.	Temperature of flue gases in front of the first superheater stage	t_4	[°C]	725	676	683	656	708	678
6.	Temperature of flue gases in front of the water heater	t_5	[°C]	623	589	592	578	609	593
7.	Temperature of flue gases in front of the turbine economizer (TuE)	t_6	[°C]	-	-	372	361	385	372
8.	Temperature of flue gases in front of the air preheater	t_7	[°C]	351	326	305	294	313	301
9.	Temp. of flue gases at the boiler outlet	t_{out}	[°C]	**223**	208	185	178	187	179
Heat receiver (superheated steam)									
10.	Feed water temperature	t_{fw}	[°C]	**164.3**	164.3	266.3	266.3	270.5	270.5
11.	Water temp. at the outlet of water heater	t_{fwo}	[°C]	**335**	326	362	360	363	361
12.	Temperature of the medium at the outlet of NRD 1	t_{NRD1o}	[°C]	**391**	391	398	399	403	404
13.	Temp.of the medium at the outlet of NRD 2	t_{NRD2o}	[°C]	**399**	399	415	419	417	421
14.	Steam temperature at the outlet of SRD	t_{SRDo}	[°C]	**415**	423	446	455	445	452
15.	Steam temp. at the outlet of VRD	t_{VRDo}	[°C]	**428**	441	469	478	466	474
16.	The amount of heat transferred in biflux	Q_{BIF}	[MW]	34.77	46.13	47.07	56.94	45.74	57.72
17.	Steam temperature at the inlet to convective superheater	t_{KPPi}	[°C]	**493**	497	502	500	499	497
18.	Steam temperature at the outlet of convective superheater	t_s	[°C]	**545**	545	545	545	545	545
Heat receiver (reheated steam)									
19.	Steam temperature at the inlet of the second reheated stage	t_{KPSP2o}	[°C]	**491**	493	489	495	485	491
20.	Steam temperature at the outlet of the second reheated stage	t_{rs}	[°C]	**545**	538	545	545	545	545

* Boiler operation with coal of greater tendency to slag.
** Boiler operation with coal of less tendency to slag

In order to allow the possibility of comparative analysis in the tables of heat balance and thermal calculation, the operating regimes with the new combustion system and the existing power of 260 MW are shown, as well as the work with the design power of 300 MW, which could not be realized before the proposed measures.

By analysing the presented results, it can be noticed that the reorganization causes lower temperatures of combustion products at the outlet of the furnace, higher power and process efficiency. It should be noted that for these reasons, the proposed reorganization of the system includes the introduction of an additional heating surface of the turbine economizer (TuE), reducing the semi-irradiated superheater and increasing the second reheater. Reconstructions of the convective superheater, the first reheater stage and the finned water heater are not necessary. In this way, it would be possible for the temperatures of the combustion products in front of the finned water heater to be close to the design ones. The reduced thermal efficiency of the existing finned water heater has led to the need to install a TuE, which would be installed instead of the third stage air preheater. By installing a turbine economizer and repairing the first and second stage air preheater in order to seal them, the temperature of the combustion products at the outlet of the steam boiler would be reduced, which would significantly improve its efficiency. This lowering of the temperature of the combustion products at the boiler outlet would enable the unit to work with the high pressure feed water heaters on. In addition, it should be noted that when using coal with a greater tendency to fouling boiler heating surfaces, with unit power greater than 280 MW, the temperature of the combustion products in front of the convective superheater at the outlet of the diversion chamber would exceed the recommended maximum value of 820 °C, which represents protection in the operation of the boiler from increased fouling of its heating surfaces and subsequent suspension of work for their cleaning.

For unit power of 300 MW, with high pressure heaters included, the temperature of the combustion products at the boiler outlet would be 187 °C, boiler efficiency would be 87.16% and the temperature of the combustion products in front of the convective superheater would be 836 °C (zone of increased risk of slagging and fouling of boiler heating surfaces). All this indicates that, when operating a boiler with coal that has a greater tendency to fouling the heating surfaces, the maximum unit power of 280 MW could be achieved, so this load (TC3a*) is shown in tab. 4. When using coal less prone to fouling, it is possible to safely achieve a design power of 300 MW with an efficiency of 87.67%.

Analysis of the boiler calculation system results

Based on the mentioned models, control CFD calculations of the furnace for the power of 260 MW were performed with the high pressure heaters turned off when burning coal with higher (UNR*) and lower (UNR**) tendency to fouling of the boiler heating surfaces, with lower heating value of 10341 kJ/kg. The results of control CFD calculations for the furnace and extended domain of the diversion chamber with convective gas channel, for the existing conventional combustion system and work with coal with a higher tendency to fouling, as the most unfavorable operating regime, are presented by appropriate temperature and concentration fields of O_2 and CO. The basic results of these calculations are shown in tab. 4, while the characteristic fields are shown in figs. 2-4. Figure 2 show the temperature fields in the central longitudinal and characteristic cross-sections of the boiler. On the longitudinal sections, it can be noticed that the thermal gradient is small, that is, that the temperature on the side of the combustion products, due to the high fouling of the screen walls, slowly decreases in the vertical direction. The cross-sections suggest that a high combustion temperature occurs in the central space between the side walls of the furnace, thus forming a flame curtain of a specific shape, composed of three prismatic segments, as shown in fig. 8. Calculations have shown that the side walls are approximately as irradiated as the front and rear wall. Analysis of the temperature field in the axial cross-sections of the burners can show markedly elevated temperatures in the areas of the front and rear wall of the furnace, which ranges between 1230 °C and 1280 °C. This phenomenon is a consequence of vortices in the corners of the main combustion zone, so that in this way, a part of the coal particles is located in the dead zones between the end burners and the front and rear wall, which locally raises the temperature. It can be easily noticed that high temperatures, up to 1180 °C, are present along the front and rear walls and in the upper parts of the furnace up to the level of 38.5 m. The highest temperatures of combustion products along the side walls occur in the lower parts of the furnace in the areas below the burner which represent the most sensitive zones of the screen walls in terms of slagging.

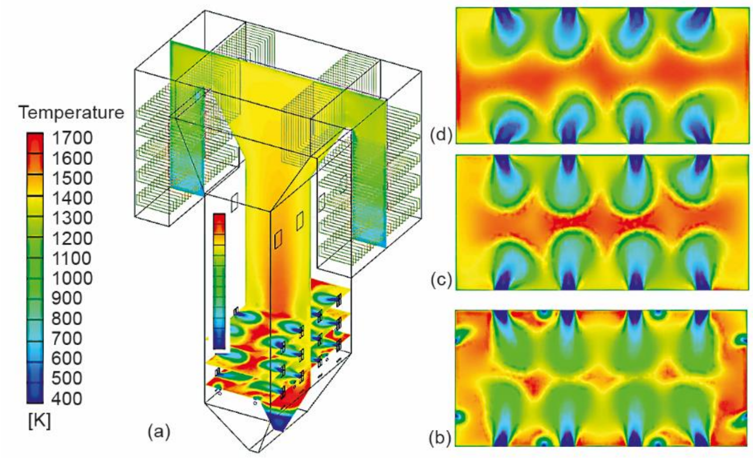

Figure 2. Temperature field in the calculation domain. Coal with a greater tendency to fouling heating surfaces (H_d = 10341 kJ/kg) for unit power of 260 MW, with HPH turned off and eight mills in operation; (a) central longitudinal section along the width of the boiler, (b) cross-section along the axis of the lower burner, (c) cross-section along the axis of the middle burner, and (d) cross-section along the axis of the upper burner (*for color image see journal web site*)

Figure 8 shows a parallel view of the temperature field in the longitudinal sections of the boiler in width and depth of the furnace, which is supplemented by a spatial representation of high temperatures in the furnace. Maximum temperatures in the boiler furnace for these operating conditions range from 1250 °C to 1400 °C. By analysing the mentioned view, it can be noticed that the maximum temperatures occur in the zones below the first level of the burner, and as a result of the increased flow of the air mixture through the lower burners. As the burners are inclined 15° towards the furnace funnel, 51% of the air mixture and secondary air from the first level cross the path through the part of the furnace funnel, so intensive combustion takes place in the zones below the burner in a field of significantly increased oxygen concentration, which results in an increase in local temperature of the combustion products. By analysing the field in fig. 8, it can be noticed that the air mixture from the lower level of the burner is significantly directed towards the furnace funnel, and in the absence of resistance in the form of combustion products moving towards the boiler outlet. Opposite to it, the coal particles of the air mixture from the second level of the burner has, at a slightly lower slope, sufficient range and path to the center of the furnace, and then continues upwards, and consequently has a shorter path and time of stay in the furnace. In the case of coal particles from the third level of the burner, this phenomenon is even more expressed, so the particles turn towards the exit from the furnace earlier. Essentially, the formed products of coal particles combustion from the first level of the burner with their impulse partially correct the input currents formed from the second and especially the third level of the burner and do not allow the coal particles to extend its path through the lower parts of the furnace. This phenomenon, conditioned by the opposite position of the burner, results in a part of the coal particles, especially the one from the upper level of the burner, partially burning in the zones above the burner where temperatures up to 1250 °C are maintained. As the amount of coal particles that is introduced into the third level of the burner is only 19% and as the combustion takes place in a field of high oxygen concentration, it mostly ends up to the level of 23.5 m. By analysing the temperature field in the longitudinal plane, it can be stated that the distribution of the air mixture by burner levels, in the ratio of 51:30:19 by mass, contributed to the lowering of the flame and its maximum temperature towards the furnace funnel. In addition, it can be stated that the second part of the flame was slightly extended due to a smaller impulse from the third level of the burner, so this distribution achieved a flame that was lowered but somewhat extended in the direction of the furnace exit. All of the above resulted in flue gas furnace outlet temperature of 1043 °C.

Figure 3 shows the oxygen field where it is clear that the combustion is organized in conditions of significantly increased concentration, and according to the coefficient of excess air of 1.24. By analysing the cross-sections through burners, it can be noticed that the way of introduction and high speeds of secondary air ensure that coal particles pass through a field of high oxygen concentration which provides fast reactions, as conventional combustion is conceived. Combustion acceleration was additionally achieved by preparing coal powder of increased fineness as shown in tab. 4, where the ratio of secondary air and air mixture velocities is also shown, amounting to 2.70 for this operating mode. An overview of the CO field in fig. 4 shows the zones along the height of the furnace, above the upper level of the burner, where the combustion mostly ends. Higher concentration of CO occurs in the zones of active combustion at the level of the burner in the central part of the furnace.

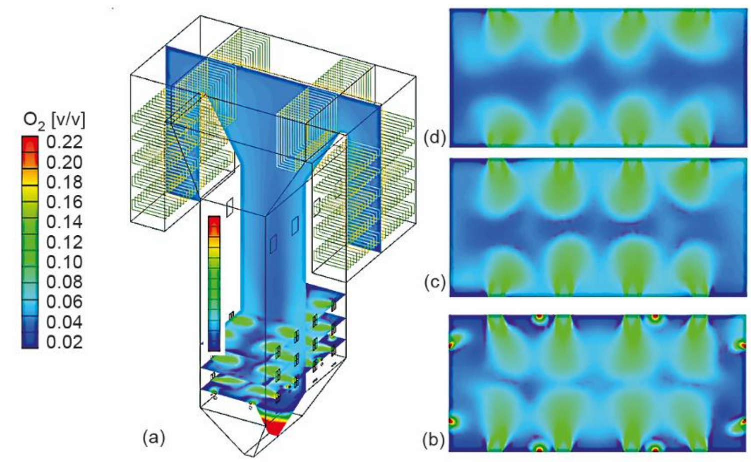

Figure 3. Oxygen field in the calculation domain. Coal with a greater tendency to fouling heating surfaces (H_d = 10341 kJ/kg) for unit power of 260 MW, with HPH turned off and eight mills in operation; (a) central longitudinal section along the width of the boiler, (b) cross-section along the axis of the lower burner, (c) cross-section along the axis of the middle burner, and (d) cross-section along the axis of the upper burner (*for color image see journal web site*)

By analysing the operating mode, with the design organization, it can be stated that the process of combustion by lowering the flame started earlier and that the maximum temperature occurs in the zone below the first level of the burner. The flame of a specific curtain shape is somewhat elongated, and calculations have shown that its irradiation towards the walls is lower than the flame that forms around the central vortex. In addition to the smaller amount of emitted energy, increased fouling from the walls represents additional resistance to absorption, so as a final result we have a high temperature of the combustion products at the end of the furnace. The increased content of oxygen and recirculated cold combustion products, as a measure of lowering the average outlet temperature of combustion products from the furnace, enabled the combustion to proceed faster and the content of nitrogen oxides to be at the level of 396 mg/Nm^3.

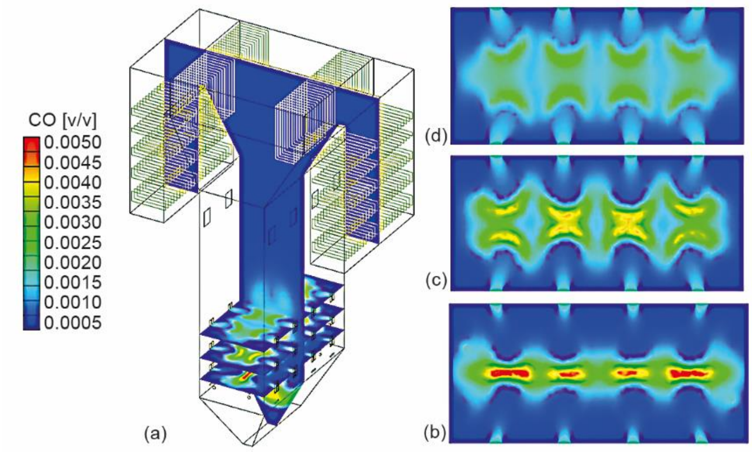

Figure 4. Carbon monoxide field in the calculation domain. Coal with a greater tendency to fouling heating surfaces (H_d = 10341 kJ/kg) for unit power of 260 MW, with HPH turned off and eight mills in operation; (a) central longitudinal section along the width of the boiler, (b) cross-section along the axis of the lower burner, (c) cross-section along the axis of the middle burner, and (d) cross-section along the axis of the upper burner (*for color image see journal web site*)

Figure 5 show the temperature fields in the central longitudinal and characteristic cross-sections of the boiler, for the most favorable reorganized operating mode (TC4**) in the combustion of coal less prone to fouling. On the longitudinal sections, it can be noticed that the thermal gradient is large, that is, that the temperature on the side of the combustion products in the vertical direction decreases significantly. The cross-sections suggest that a high combustion temperature occurs in the central space around the central vortex and that in this way an elliptical-circular flame is formed at the base. The accelerated combustion achieved by the new combustion organization suggests that there is no need to tilt the burner towards the furnace funnel. Calculations have shown that the flame, which is formed due to the new tangential orientation of the burner, has a larger surface area and irradiation towards the furnace screens. By analysing the temperature field in the axial cross-sections of the burners, less pronounced zones of elevated temperature of combustion products can be observed, which range between 1280 ^{o}C and 1350 ^{o}C. As the power of the central vortex is dominant, there is no retention of coal particles around the local vortices in the corners of the main combustion zone, so there is less danger of additional thermal stress and intense local fouling in these zones, which was expressed in design conditions. In fig. 5, it can be easily noticed that high

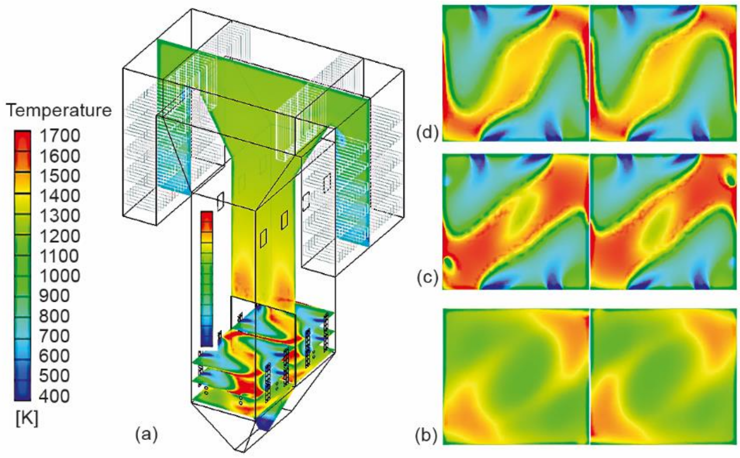

Figure 5. Temperature field in the calculation domain. Coal with less tendency to fouling heating surfaces (H_d = 10341 kJ/kg) for unit power of 300 MW, with HPH turned on and eight mills in operation; (a) central longitudinal section along the width of the boiler, (b) cross-section above the funnel, (c) cross-section along the axis of the lower floor of the burner, and (d) cross-section along the axis of the upper floor of the burner (*for color image see journal web site*)

temperatures, up to 1170 ^{o}C, are present along the screen walls in the upper parts of the furnace up to a level of 30.4 m. The highest temperatures of the combustion products along the walls occur in the lower parts of the furnace in the main combustion zone. The field shown suggests that the temperatures of the combustion products directly next to the partition wall are high. Zones of such elevated temperatures represent the most sensitive parts of the screen walls in terms of slag, but they are narrower and of slightly lower values of temperatures than when working in the design conditions of the boiler. Figure 9 shows a parallel view of the temperature field in the longitudinal sections of the boiler in width and depth of the furnace, which is supplemented by a spatial representation of high temperatures in the furnace. The analysis of the mentioned view shows that the maximum temperatures occur in the burner zones as a result of the extended time that the particle spends at this level due to the increased path it travels in the space around the central vortex. Intensive combustion takes place on this road in the burner zones in the field of significantly increased oxygen concentration, which results in a large increase in the local temperature of the combustion products. By analysing the field in fig. 9, it can be noticed that the air mixture from both levels of the burner is directed horizontally. In addition, it can be stated that the partition wall divided the furnace, in the main zone, into two equal units of an approximately square cross-section, which enable the formation of two equal central flames, which are cooled more intensely due to their geometry. It has been shown that the existence of a partition wall is in the function of maintaining the desired flame geometry and that its influence is negligible in terms of the total amount of heat transferred. All of the above resulted in increased heat flux through the screen walls of the furnace and a lower mean outlet temperature of the combustion products of 922 ^{o}C.

Figure 6 shows the oxygen field where it is clear that the combustion is organized in conditions of significantly increased oxygen concentration, and according to excess air in the furnace of 1.20. By analysing the cross-sections through the burners, it can be noticed that the way of introduction and sufficiently high speed of secondary air ensure that the coal particles pass through a field of high oxygen concentration which provides fast reactions, which is how

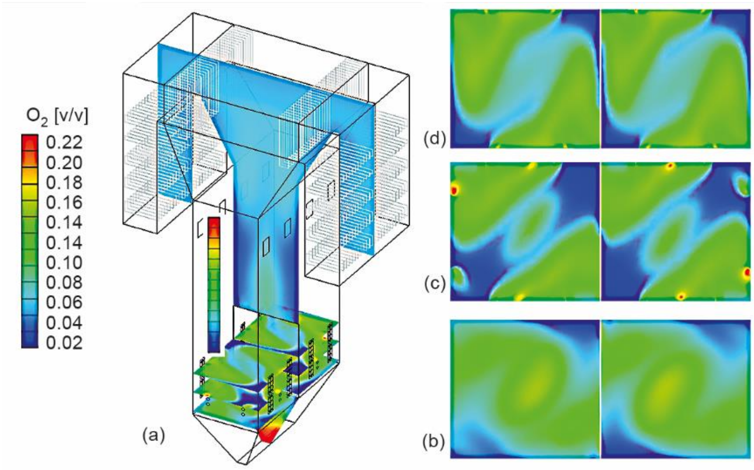

Figure 6. Oxygen field in the calculation domain. Coal with a greater tendency to fouling heating surfaces (H_d = 10341 kJ/kg) for unit power of 300 MW, with HPH turned on and eight mills in operation; (a) central longitudinal section along the width of the boiler, (b) cross-section along the axis of the lower burner, (c) cross-section along the axis of the middle burner, and (d) cross-section along the axis of the upper burner (*for color image see journal web site*)

conventional combustion is conceived. It can also be noticed that the zones of the central vortex, in which oxygen is consumed, are the ones in which the main part of the combustion process takes place. Combustion acceleration was additionally achieved by preparing coal powder of increased fineness, as shown in tab. 4. An overview of the carbon monoxide field in fig. 7 shows the zones along the height of the furnace, above the partition wall, where the combustion ends to the greatest extent. Higher concentrations of carbon monoxide appear in the zones of active combustion at the level of the burner, which is expected.

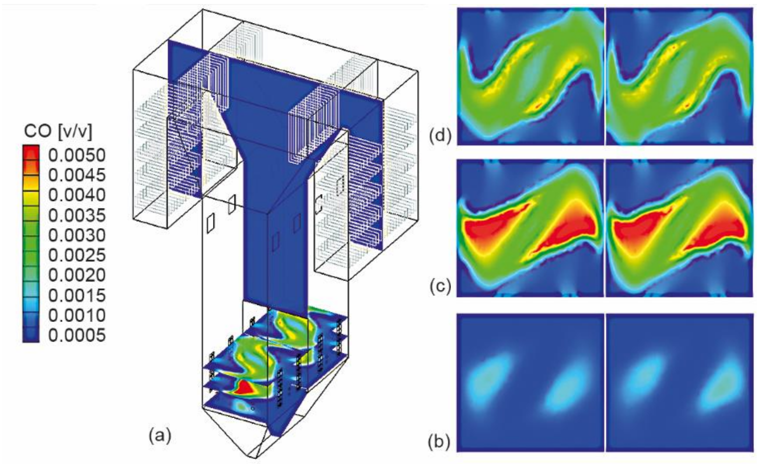

Figure 7. Carbon monoxide field in the calculation domain. Coal with a greater tendency to fouling heating surfaces (H_d = 10341 kJ/kg) for unit power of 300 MW, with HPH turned on and eight mills in operation; (a) central longitudinal section along the width of the boiler, (b) cross-section along the axis of the lower burner, (c) cross-section along the axis of the middle burner, and (d) cross-section along the axis of the upper burner (*for color image see journal web site*)

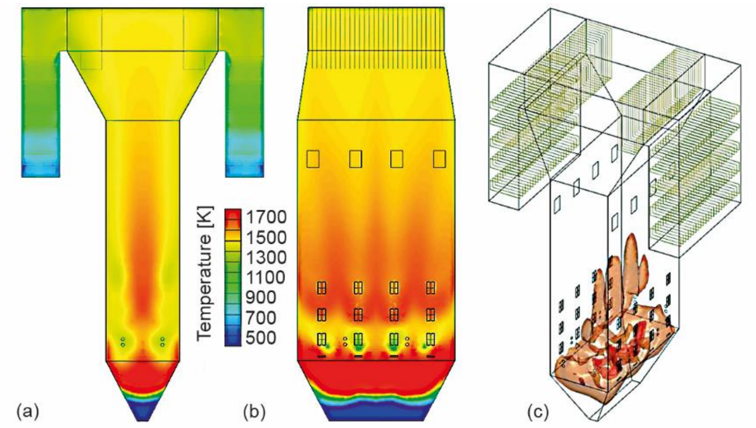

Figure 8. Temperature field and spatial representation of high temperatures in the calculation domain. Coal with a greater tendency to fouling heating surfaces (H_d = 10341 kJ/kg) for unit power of 260 MW, with HPH turned off and eight mills in operation; (a) central longitudinal section along the width of the boiler, (b) central longitudinal section along the depth of the boiler, and (c) isothermal surfaces in the range 1523-1673 K (*for color image see journal web site*)

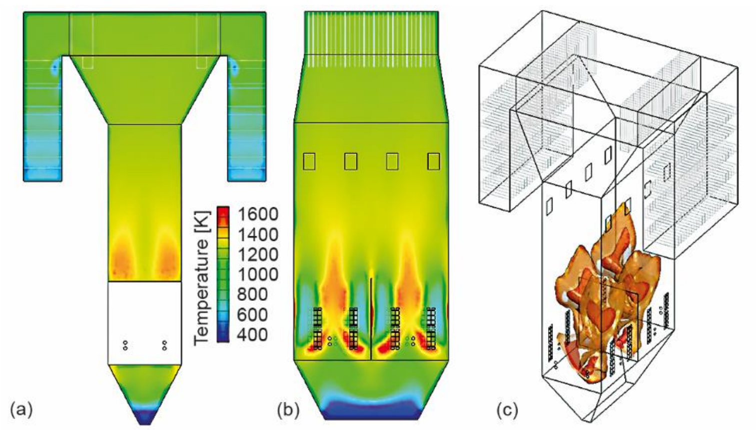

Figure 9. Temperature field and spatial representation of high temperatures in the calculation domain. Coal with a greater tendency to fouling heating surfaces (H_d = 10341 kJ/kg) for unit power of 300 MW, with HPH turned on and eight mills in operation; (a) central longitudinal section along the width of the boiler, (b) central longitudinal section along the depth of the boiler, and (c) isothermal surfaces in the range 1553-1623 K (*for color image see journal web site*)

By analysing the operating mode, with the reorganized system, it can be stated that the combustion process using new burners and the way of introducing air mixture and air led to the acceleration of the combustion process and that the maximum temperature occurs in the zone at the burner level. The flame has a specific shape of the tube formed around the central vortex, and calculations have shown that its irradiation towards the walls is increased in relation to the flame curtain that is formed in the design conditions of combustion. The increased amount of emitted energy with the design level of fouling on the side of the screen walls as a result has a design low temperature of the combustion products. It can be stated that the introduction of a new combustion organization, in this way, significantly reduced the temperature of the combustion products at the end of the furnace, so the steam boiler can achieve higher power up to 300 MW. Prolonged time the particle spend in the furnace with increased content of oxygen and recirculated cold combustion products, enabled the combustion to take place in conditions that the content of nitrogen oxides is at the level of 451 mg/Nm^3 and during the operation of the block of 300 MW with high pressure heaters included.

Table 4. Extracts of boiler calculation system

No.	Name	Mark	Unit	Unit power [MW]					
				260				280	300
				without HPH		with HPH			
				UNR*	**UNR****	TC1*	TC2**	TC3$_a$*	TC4**
1.	Excess air at the furnace outlet	α_l	[–]	1,240	1,240	1,240	1,240	1,200	1,200
2.	Number of mills in operation	m	[–]	8	8	8	8	8	8
3.	Fineness of grinding coal powder	R_{1000}	[%]	2,20	2,20	2,20	2,20	2,20	2,20
		R_{90}	[%]	50	50	50	50	50	50
4.	Nitrogen content in working coal	N^r	[%]	0,81	0,81	0,81	0,81	0,81	0,81
5.	Ratio of secondary air veloci-ty and air mixture	w_{sa}/w_{am}	[–]	2,70	2,27	2,68	2,28	2,54	2,69
6.	Recirculation rate of cold gases	r_2	[–]	0,145	0,145	0,130	0,130	0,125	0,120
7.	Mean temperature of com-bustion products at the end of the furnace	t''_l	[°C]	1044	968	919	886	938	922
8.	Temperature of flue gases behind the semi-irradiated superheater	t_1	[°C]	876	815	821	791	841	828
9.	Temperature of flue gases in front of convective superheater	t_2	[°C]	852	791	799	771	819	806
10.	Concentration of oxygen in dry flue gases	$(O_2)_r$	[% v/v]	4,08	4,07	4,08	4,08	3,82	3,59
11.	Concentration of CO at reference conditions	$(CO)_r$	[mgN^{-1}m^{-3}]	44	46	25	30	33	37
12.	Concentration of NO_x at reference conditions	$(NO_x)_r$	[mgN^{-1}m^{-3}]	396	378	426	417	436	451

[a] Reduced power operation due to maintaining the flue gases temperature at the entrance to the convective heating surfaces.

The energy analysis of the plant operation can show that due to the change of excess air coefficient, increased sealing and application of turbine economizer, there was an increase in the efficiency of the boiler and fuel consumption was reduced for the same boiler operation loads before and after the reorganization, as shown in tab. 2. In addition, it can be stated that the degree of efficiency decreases with the reduction of the load, but that it is always higher than when operating the boiler in the current non-reorganized working conditions. Thus, from the aspect of plant efficiency, the most favorable regime is TC4**, when the boiler works with nominal production, reaches the power of 300 MW and coal has a lower tendency to fouling. By applying the coal particles combustion process set up in this way, the temperatures of the combustion products at the end of the furnace are significantly reduced and are lower than at lower unit power in UNR operating modes. This phenomenon happens as a result of the increase in heat fluxes in the furnace in new conditions of its operation. The temperature of the combustion products at the end of the furnace decreases, as expected, with less fouling of the furnace screens. As a result of this change in the furnace by further energy transfer, the temperatures of the combustion products at the outlet of the semi-irradiated superheater differ significantly from the operation of the boiler with the current combustion system, and as a result, the boiler does not have the danger of fouling the convective heating surfaces at the entrance of which the temperatures of the combustion products are around 800 °C, after the proposed changes. This phenomenon, under the existing working conditions, affected the limitation of operation, which means that the plant usually worked with reduced unit power. Thus, also from the aspect of work safety, the new organization of combustion leads to its growth. Table 4 shows the extracts of the calculation system which present the main boundary conditions and the contents of nitrogen oxides in the combustion products. It can be stated that the increase in power led to an increase in the content of nitrogen oxides, which is expected as the conventional concept of combustion was maintained and the retention time of coal particles in the furnace was extended.

Conclusion

By applying the procedures of connecting integral and differential mathematical models, a new organization of the combustion process in TPP Ugljevik was tested, thus design the geometry and method of implantation new burners and the partition wall of the furnace. In this way, two central vortices were chosen as optimal for the basis of the new same directions flame, from the aspect of temperature field symmetry and the absence of particularly unfavorable zones of high local temperature in the area of screen walls. Such boundaries of the furnace space, in the main combustion zone, enable the formation of two equal central flames, which, due to their geometry, emits energy more intensively.

The performed calculations showed that the proposed reorganization of the process, in all test operating situations, provides a more efficient operation of the plant, which is a consequence of increased heat flux in the furnace, improved sealing and additional heating surfaces. The presented analysis shows that this reorganization of the system can achieve design power of 300 MW with increased plant operation safety when the temperatures of combustion products at the entrance to convective heating surfaces have a permissible value of up to 820 °C. In the case of using coal with an increased tendency to fouling, the maximum power that can be safely achieved is 280 MW.

Calculations additionally showed that with the retained high oxygen content and cold gas recirculation rate, increased fineness of coal powder and prolonged time particles spend in the furnace, combustion is accelerated and the content of nitrogen oxides increases, depending on the workload and fouling of screen walls, from calculations additionally showed that with the retained high oxygen content and recirculated cold combustion products, increased fineness of coal powder and particles furnace residens time, combustion is accelerated and the content of nitrogen oxides increases, depending on the workload and fouling of screen walls, from 426-451 mg/Nm^3. As before the proposed measures, there is no significant amount of residual carbon monoxide in the combustion products.

Acknowledgment

This work has been supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (Project: Modern approach to improvement process in existing steam boilers in order to increase energy and environmental efficiency, No. Contract:451-03-68/2022 – 14/200105).

References

[1] Liu, Y., *et al*., Numerical Investigation of Air-Staged Combustion Emphasizing Char Gasification and Gas Temperature Deviation in a Large-Scale, Tangentially Fired Pulverized-Coal Boiler, *Applied Energy, 177* (2016), Sept., pp. 323-334
[2] Yang, Y.-H., *et al*., Effects of Detailed Operating Parameters on Combustion in Two 500-MWe Coal-Fired Boilers of an Identical Design, *Fuel, 144* (2015), Mar., pp. 145-156
[3] Drosatos, P., *et al*., Numerical Investigation of Firing Concepts for a Flexible Greek Lignite-Fired Power Plant, *Fuel Processing Technology, 142* (2016), Feb., pp. 370-395
[4] Stupar, G., *et al*., Assessing the Impact of Primary Measures for NO_x Reduction on the Thermal Power Plant Steam Boiler, *Applied Thermal Engineering, 78* (2015), Mar., pp. 397-409
[5] Stupar, G., *et al*., Air Staging Application Effects on Overall Steam Boiler Operation, *Thermal Science, 23* (2019), Suppl. 5, pp. S1559-S1574
[6] Stupar, G., *et al*., Predicting Effects of Air Staging Application on Existing Coal-Fired Power Steam Boiler, *Applied Thermal Engineering, 149* (2019), Feb., pp. 665-677
[7] Sun, W., *et al*., Gas-Particle Turbulent Flow of Foursquare Tangential Jets in a Simplified Pulverized-Coal Firing Boiler, *Fuel Processing Technology, 29* (2018), 6, pp. 1463-1473
[8] Zha, Q., *et al*., Numerical Evaluation of Heat Transfer and NO_x Emissions under Deep-Air-Staging Conditions within a 600 MWe Tangentially Fired Pulverized-Coal Boiler, *Applied Thermal Engineering, 78* (2017), Apr., pp. 397-409
[9] Belošević, S., *et al*., Modeling of Pulverized Coal Combustion for In-Furnace NO_x Reduction and Flame Control, *Thermal Science, 21* (2017), Suppl. 3, pp. S597-S615
[10] Stupar, G.**,** Modeling of Processes in Utility Steam Boiler with Air Staging, Ph. D. thesis, University of Belgrade, Belgrade, 2016 (in Serbian)
[11] Tucakovic, D., *et al*., *Development of Mathematical Models of Main Plants with Control Calculation, Analysis of Work and Measures to Improve the Situation of TPP Ugljevik – Boiler Plant* (in Serbian), University of Belgrade – Faculty of Mechanical Engineering, Belgrade, 2020
[12] ***, COTES, Technical Report on the Results of Inspections and Thermal Tests of the Boiler Unit Type P-64 Power Unit 300 MW TPP Ugljevik, Novosibirsk 2019
[13] ***, TPP Ugljevik (General Characteristics of the Boiler, Elemental Analysis of Warranty and Used Coals, Reconstruction of Boiler Heating Surfaces, Adjustment of Boiler Equipment and Elements)
[14] Tucakovic, D., *et al*., *Development of Technical Solution for Modernization of TPP Ugljevik, Financial Evaluation and Consulting Services – Boiler Plant* (in Serbian), University of Belgrade – Faculty of Mechanical Engineering, Belgrade, 2021
[15] Brkic, Lj., *et al*., *Thermal Calculation of Steam Boilers* (in Serbian), University of Belgrade, Faculty of Mechanical Engineering, Belgrade, 2015

Paper submitted: July 7, 2022
Paper revised: December 6, 2022
Paper accepted: December 30, 2022