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Investigation of a Combustion Chamber Operation in Coal-firing Boiler Using Simulation Modeling Methods

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Abstract

One of the thermal power plants in Bulgaria firing imported coals is TPP “Ruse East”. In 1971 a mono block power unit with a waste heat boiler and nominal steam generation of 365 t/h and 110 MW electrical output turbine started operation. The exploitation of this power unit in present conditions requires compliance with a number of environmental standards as well as an assessment of its performance parameters. In-depth research of the processes in the combustion chamber depends on advanced methods such as computational simulation and also on conventional measurement tests. With the help of specialized software for combustion processes investigation an evaluation of the impact of different operational and structural influences on the coal burning degree and the generated concentrations of nitrogen oxides is performed.

Keywords: *steam boiler; combustion chamber; combustion model; char combustion degree; nitrogen oxides*

1. Introduction

There are two methods for investigation of the conditions and the processes in the combustion chambers:

- First one is preparation of experimental installation and performing numerous measurements [1,2];
- The second is simulation modeling of the processes occurring in the combustion chamber [3,4].

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Computational level of complexity varies with the calculation of the total impact on the combustion depending on the inlet and the outlet conditions until determination of the temperature and concentration planes in the furnace.

During continuous operation simulation modeling as an investigation technique requires less time and resources compared to experimental tests. Because of this simulation modeling has established itself as a mean for investigation where the number of parameters of interest is greater than what experimental techniques allow. Moreover particle behavior and aerodynamics in the combustion zone near the burner of real furnaces cannot be easily represented in a scale model. This needs to be kept in mind during the results analyzing process obtained from experimental scale models – for example in case of the flame stability and NO_x generation predictions. Phenomena extrapolation near burners is mostly relieved by reliable mathematical model. Simulation modeling's only drawback is that the output data are as accurate as the real processes are represented within the software [5].

2. Materials and methods

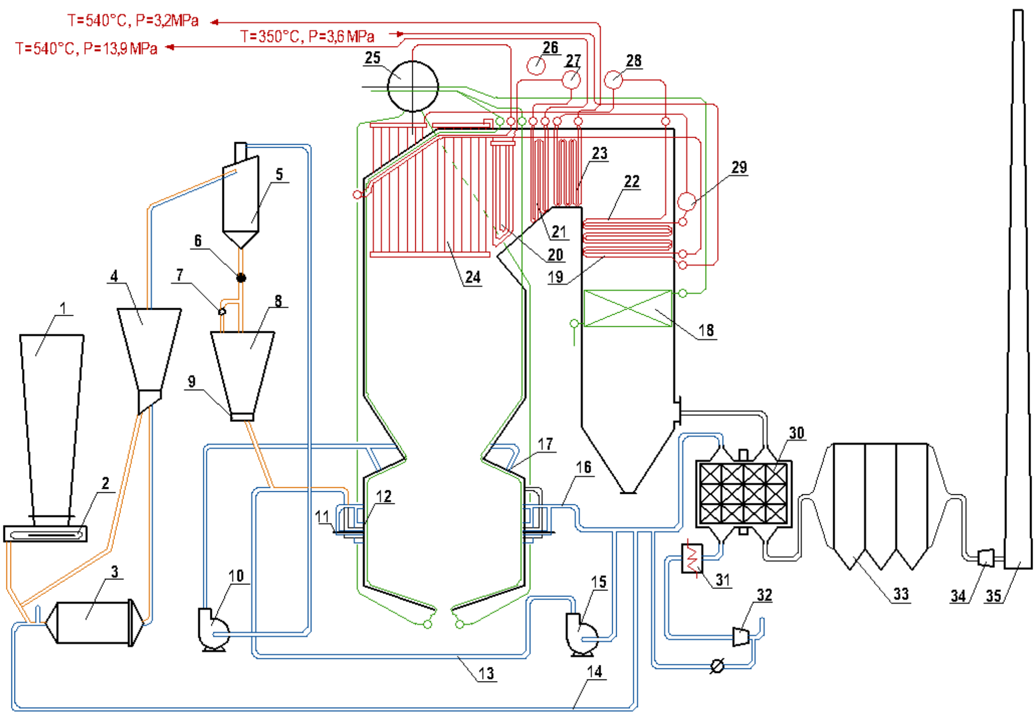
2.1. Materials

The object of investigation is boiler type 1B-365-139. It is steam generator with natural circulation, one steam drum firing pulverized sub-bituminous coal with liquid slag discharge – Figure 1. The combustion chamber has rectangular semi-open shape with dimension *7 545 mm x 11 985 mm* and narrowing on 6 m from the furnace bottom with cross-section dimension *3 950 mm x 11 895 mm* which divides the combustion chamber into pre-furnace and cooling chamber. The pre-furnace consists of fin-tubes with special fireproof lining. Furnace bottom has screen tubes on front and rear walls. The slag outlet is situated in the geometrical center. Above the narrowing the cooling gas chamber is located at the top of which the screen tubes on the rear wall form aerodynamic plate designed for improved aerodynamics of the gas flow on the combustion chamber outlet. The boiler has 10 main swirl burners located on level *3,17 m* from the bottom. Furnace horizontal cross-section is rectangle with dimensions *11,985 m x 7,545 m*. Five of them are placed on the front wall and five on the rear wall that are longer than the right and left side – Figure 2. In Figures 3 and 4 are show main and vapor burner sectional cut. The boiler is equipped with 8 vapor burners – 4 on each of the main and vapor burners side. They are directed downwards to the smelting furnace.

2.2. Methods

2.2.1. Organized air supply distribution

Part of it is fed on the mill's inlet and functions as a drying agent during pulverizing as well as transportation of pulverized coal through the cyclone. This air ("air for the mill") along with the finest particles and the evaporated moisture enters vapor burners. On the other hand the air transporting the main part of coal dust is called "primary air" and the additional one fed through all burners (main and vapor) is called "secondary air".



1 - Raw coal bunker
2 - Raw coal feeder
3 - Mill
4 - Classifier
5 - Cyclone
6 - Tourniquet
7 - Coal dust hopper
8 - Coal dust bunker
9 - Coal dust doser
10 - Mill fan
11 - Oil burner
12 - Coal burner
13 - Primary air
14 - Air to mills
15 - Primary air fan
16 - Secondary air
17 - Vapor burner
18 - Economizer
19 - Super heater low pressure- 1
20 - Super heater high pressure –3
21 - Super Heater high pressure – 4
22 - Super heater high pressure – 1
23 - Super heater low pressure – 2
24 - Super heater high pressure – 2
25 - Steam drum
26 - Desuperheater stage 2
27 - Desuperheater stage 3
28 - Desuperheater stage 1
29 - Desuperheater stage 4
30 - Regenerative air heater
31 - Air heater
32 - Secondary air fan
33 - Electrostatic precipitator
34 - Induced draft fan
35 - Stack

Fig.1 Boiler type 1B-365-139 design

All cross-sections of fuel and air ducts are shown in Table 1.

Table 1. Fuel and air ducts cross-sections

	Fuel duct	Secondary air	Air to vapor burners	Fuel duct vapor burners
Count	10	10	8	8
Cross-section per duct, m^2	0,17	0,43324	0,0168	0,063
Total cross-section, m^2	1,7	4,3324	0,1344	0,504

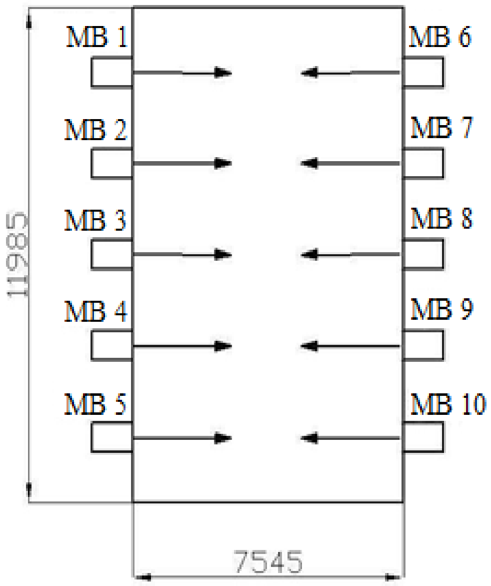


Fig.2 Vapor burners view from furnace

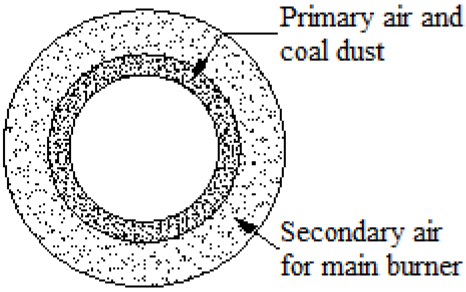


Fig.3 Main burners view from furnace

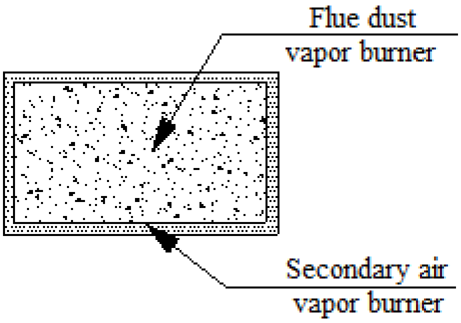


Fig.4 Vapor burners view from furnace

The boiler is designed for firing Donetsk coals type T. The chemical composition and the net heating value of the fuel are shown in Table 2.

Table 2. Donetsk coals type-T composition

C^r, %	H^r, %	N^r, %	O^r, %	S^r, %	A^r, %	W^r, %	LHV, kJ/kg
70,04	2,78	1,03	1,35	0,42	16,6	6,0	26 167

2.2.2. Preparation of computational model and validation

According to the constructional design data a numerical model of the furnace is prepared. The model is limited to the second narrowing of the combustion chamber at level 16,2 m. This simplification is made in order for the computational time to be reduced. Simulated furnace volume is divided into 390 000 basic volumes – computational mesh which is an orthogonal one. The density differs in various areas of the model volume. At the burner area it is finer than the furnace outlet area due to the degree of process complexity (fuel-air mixing and ignition). For more accurate results the mesh density has to be greater. General view of the generated mesh for the model investigations is presented in Figure 5.

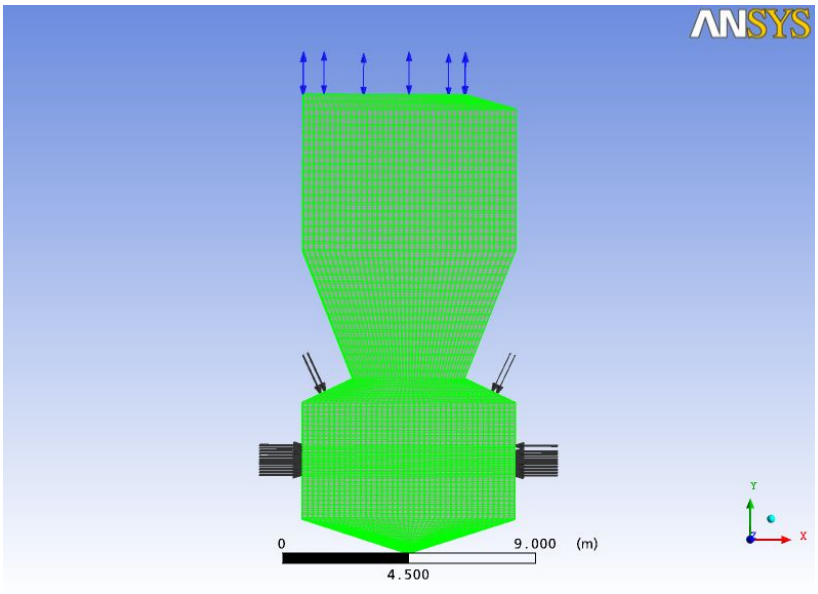


Fig.5 Generated mesh

Besides a correct drawing of the furnace construction to create a proper model the inlet flows values need to represent the real conditions [6]. On 100% load the boiler's fuel consumption is *42,5 t/h (11,805 kg/s)* with 20 % of the coal dust fed through 8 vapor burners *(2,361 kg/s, 0,2951 kg/s per burner)* and 80 % enters the furnace through 10 main burners *(9,444 kg/s, 0,9444 kg/s per burner).* Average particle diameter in main burners is *57 μm* respectively *31 μm* in vapor burners. Air volume temperature and volume flows are shown in Table 3.

Table 3. Air flow and respective temperatures

	Volume flow, Nm^3/h	Temperature, ^oC
Primary air, transporting coal dust to main burners	150 000	200
Secondary air to main and vapor burners	165 000	335
Air to mill, transporting coal dust to vapor burners	45 000	130
Total volume organized air supply	360 000	-

Considering the flue dust flows and burners cross-sections the velocities of the flows entering the furnace are defined – Table 4.

The velocities, respectively flows, are set as input data (initial conditions) in the simulation program. Using the simulation features of ANSYS CFX the investigation is realized and the obtained results are numerical and graphic. Thus we were able to acquire accurate values regarding flow velocity, concentration of volatiles, char, oxygen, combustion products near the screen tubes or any given volume and plane. Such large amount of information can hardly be obtained with the means of measurements on site. In order to validate the generated numerical model a comparative analysis between two different methods characterizing the operation of the combustion chamber – results from design calculations and model results is performed [7].

Design fuel data is used for validation of the model:

- Adiabatic temperature in furnace – $T_A = 2\,100 \quad °C;$
- Flue gas temperature on the outlet of smelting furnace – $T_P^{'} = 1785 \quad °C;$
- Flue gas temperature before SH 4 (aerodynamic narrowing) – $T_p = 1\,237 \quad °C;$
- Emissivity - $a_T = 0,812;$
- Thermal volume load of the pre-furnace - $q_V^{pf} = 186 \, {kW}/{m^3}$;
- Thermal volume load of the cooling aria - $q_V^{ca} = 171 \, {kW}/{m^3}$.

Table 4. Air flows velocities

	Primary air to main burners	Secondary air to main burners	Secondary air to vapor burners	Air to mill transporting coal dust to vapor burners
Velocity, m/s	32,6	17	17	35,78

A comparison between design and model data is presented in Table 5.

Table 5. Deviations between design and model data

No	Parameter	Dimension	Design	Model	Deviation, %
1	Heat taken by smelter screen walls	MW	58	61,4	5,9
2	Heat taken by screen walls between the two narrowing	MW	65	68,5	5,4
3	Heat taken by furnace screen walls	MW	123	129,9	5,6
4	Flue gas enthalpy on furnace outlet	MW	212	204,0	-3,8
5	Heat released in furnace	MW	335	333,9	-0,3
6	Flue gas temperature on smelter outlet	K	2058	1985	-3,5
7	Flue gas temperature in aerodynamic plate	K	1510	1440	-4,6

The results [8] shows that the model is adequate i.e. describes accurately enough the processes in furnace and through it a further simulation investigation for assessment of different parameters impact on the combustion can be performed [9,10].

3. Model investigations

A numerous process investigations divided in 3 groups are performed using the validated model:

3.1. Group I – model investigations at different quantity organized air supply

- $V_{air} = 317\,000\ Nm^3/h$;
- $V_{air} = 360\,000\ Nm^3/h$;
- $V_{air} = 385\,000\ Nm^3/h$.

3.2. Group II – model investigations at different ratio primary air/ total air

- $V_{primary}/V_{total} = 0{,}42$ and $V_{secondary}/V_{total} = 0{,}44;$
- $V_{primary}/V_{total} = 0{,}37$ and $V_{secondary}/V_{total} = 0{,}49;$
- $V_{primary}/V_{total} = 0{,}32$ and $V_{secondary}/V_{total} = 0{,}54.$

3.3. Group III – model investigations with additional over-fire system

4. Results and discussion

4.1. Group I model investigations

4.1.1. Initial conditions for coal-firing at different quantity organized air supply

- Case 1.1 – The total amount of organized air supply is $V_{air} = 317\,000\ Nm^3/h$ and the distribution is: *14 %* as drying and transporting agent to vapor burners, *47 %* as primary and *37 %* as secondary air. The remaining *2 %* are fed to vapor burners;

- Case 1.2 – The total amount of organized air supply is $V_{air} = 360\,000\ Nm^3/h$ with distribution: *12 %* as drying and transporting agent to vapor burners, *44 %* as primary and *32 %* as secondary air. The remaining *2 %* are fed to vapor burners;
- Case 1.3 – The total amount of organized air supply is $V_{air} = 385\,000\ Nm^3/h$ distributed: *11 %* as drying and transporting agent to vapor burners, *39 %* as primary and *48 %* as secondary air. The remaining *2 %* are fed to vapor burners.

The following parameters are the same for all cases above:

- Pulverized coal fineness for main zone is $57\ \mu m$ and $31\ \mu m$ for vapor zone;
- Fuel consumption is $B = 42{,}5\ t/h$ with lower heating value – Table 6.

Table 6. Coals composition

C^r, %	H^r, %	N^r, %	O^r, %	S^r, %	A^r, %	W^r, %	LHV, kcal/kg
74,82	3,59	1,84	2,93	0,42	11,4	5,0	6830

4.1.2. Group I results from model investigations

The obtained results from the tests at different quantity organized air supply are:

1. The higher amount of air clearly results in increased oxidizer share along furnace height as Figure 6 clearly shows. Organized air flow to furnace in real operation at this moment is around *300 000 ÷ 320 000* Nm^3/h. The amount of *360 000* Nm^3/h will guarantee excess air factor $\alpha''_{fc} \in (1{,}15 \div 1{,}20)$ on the furnace outlet. In this regard *380 000* Nm^3/h air will lead to $\alpha''_{fc} = 1{,}25$;
2. For the three considered cases the maximal temperature values are obtained in the zone above main burners. In this case with total air flow of *360 000* Nm^3/h the temperatures in the furnace are highest. Increasing organized air supply to *380 000* Nm^3/h the maximal temperature is lower – the greater amount of air is cooling the flue gas;
3. For those three cases the volatiles are burning out completely – unburned fuel losses are not present;
4. The higher amount of air determines better fuel burning. Figure 7 illustrates that the amount of fully burned char increases with higher organized air supply, respectively the loss from unburned fuel (mechanically) decrease;
5. As expected the main portion of nitrogen oxides mass flow forms between level *2÷6 m* (from the burners to the smelter outlet) – Figure 8. Naturally highest NO concentration and mass flow are present with the highest amount of organized air supply – Figure 9. The reason is that Zeldovich mechanism leads to higher nitrogen oxides concentration with higher excess air.

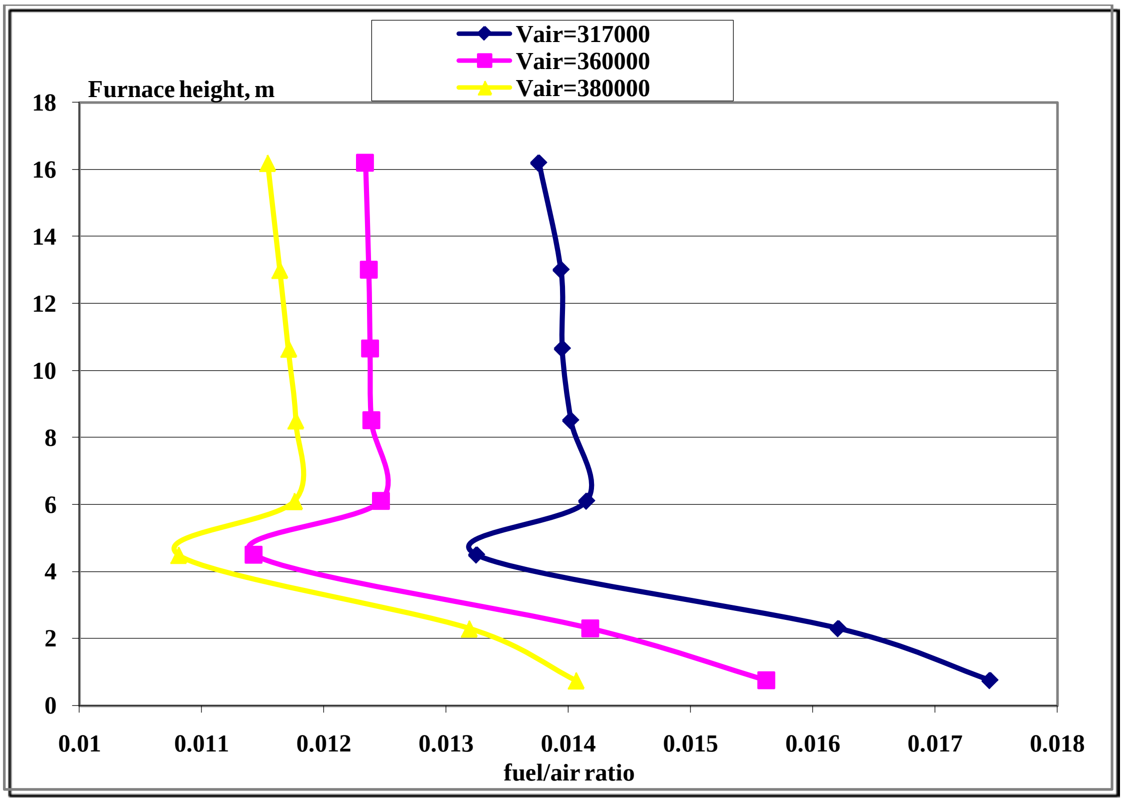


Fig.6 Fuel/air ratio variations along combustion chamber height

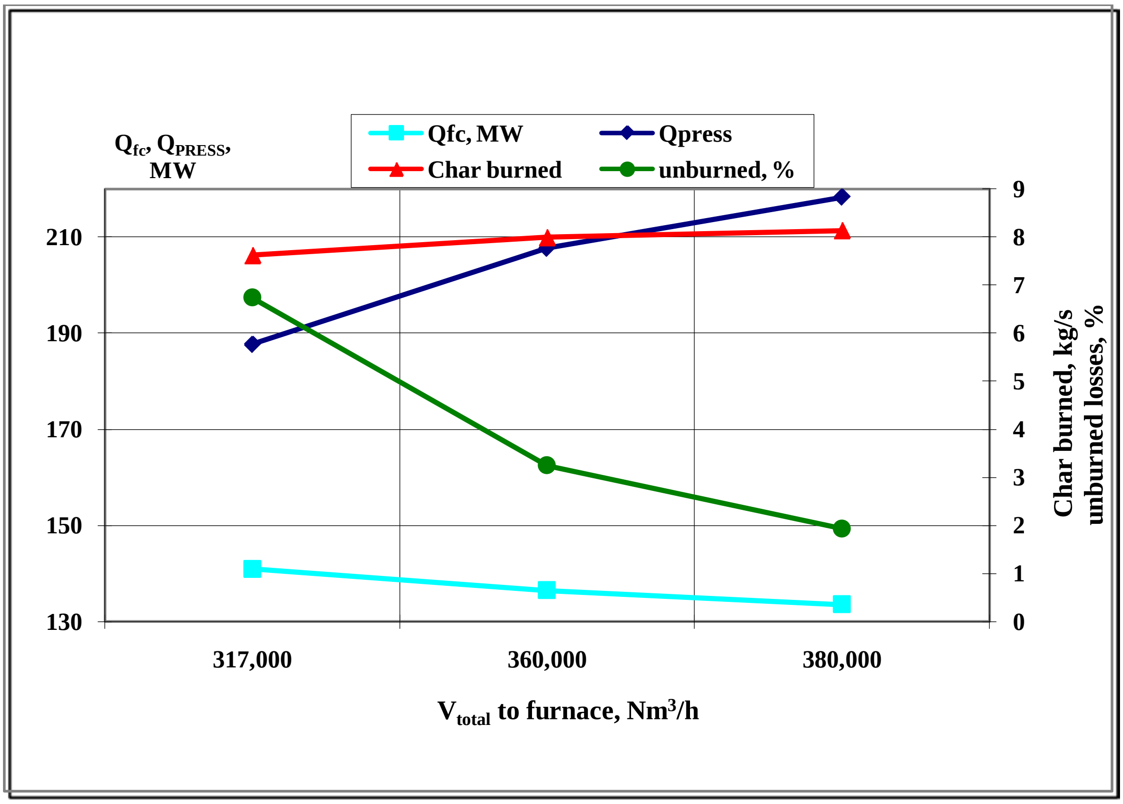


Fig.7 Combustion parameters variations at different organized air supply

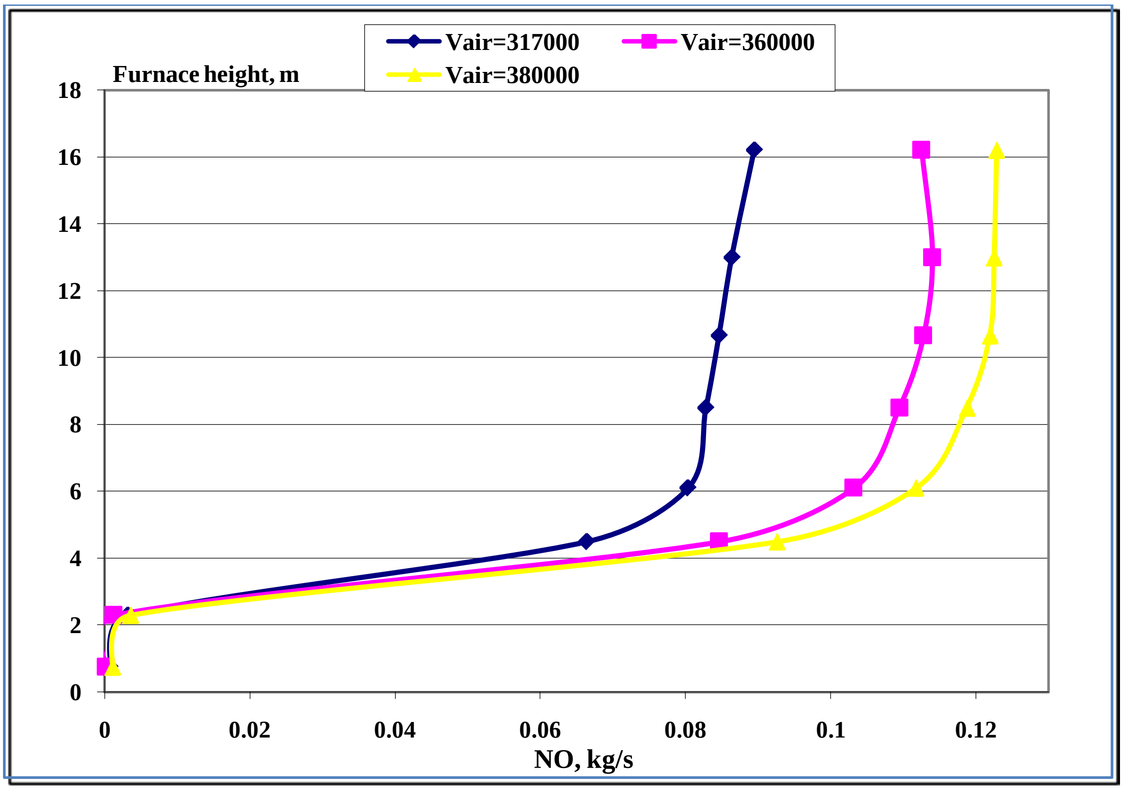


Fig.8 NO deviation along furnace height at different organized air supply

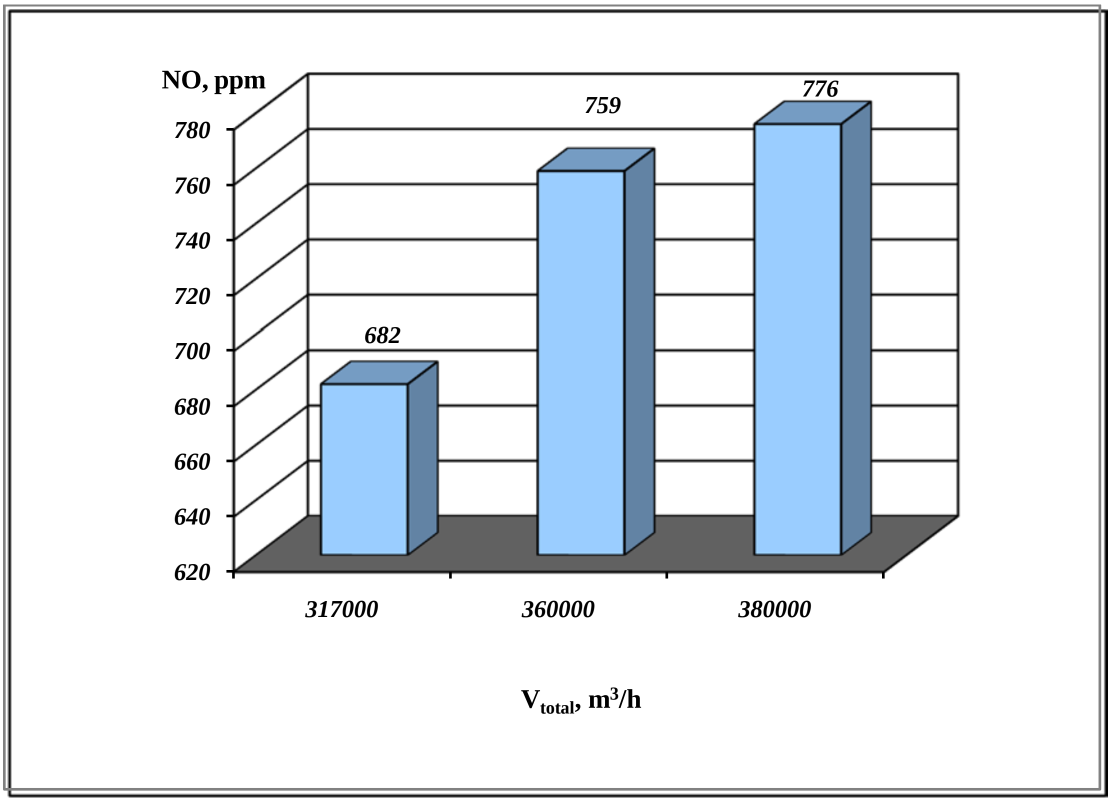


Fig.9 NO concentration on the boiler outlet at different organized air supply

4.2. Group II model investigations

4.2.1. Initial conditions for coal-firing at different ratio primary/secondary air

One of the possible effects that can be applied to the operation of this type of boiler is changing the portion of the air fed as primary (respectively secondary) during constant air flow. Surely the deviation range needs to be accurately selected – it is limited by the sufficient amount of air as primary that can ensure reliable coal dust transportation to the burners. The following 3 cases are considered:

- Case 2.1 - $V_{primary}/V_{total} = 0{,}42$ and $V_{secondary}/V_{total} = 0{,}44;$
- Case 2.2 - $V_{primary}/V_{total} = 0{,}37$ and $V_{secondary}/V_{total} = 0{,}49;$
- Case 2.3 - $V_{primary}/V_{total} = 0{,}32$ and $V_{secondary}/V_{total} = 0{,}54.$

The following parameters are the same for all cases above:

- Organized air supply flow, $V_{air} = 360\,000\ Nm^3/h$;

- Coal consumption, $B = 42{,}5\ t/h$;

- Air flow for coal dust drying and transportation to vapor burners is *12 %* of the total organized air supply;

- Combustion air to vapor burners – *2 %*;

- Average coal fineness in main burners - *57 μm;*

- Average coal fineness in vapor burners - *31 μm.*

4.2.2. Group II results from model investigations

Reduction in $V_{primary}/V_{total}$ ratio means a greater portion of the organized air supply is fed as secondary, i.e. primary air decreases. The results can be summarized as follows:

1. A clear trend is observed – by increasing secondary air portion on account of primary one, the temperatures in the furnace also increase – Figure 10;
2. Higher temperatures in the combustion chamber results in higher amount of fully burned char – reduced unburned losses as shown in Figure 11;

3. It is necessary the amount of organized air supply as primary and secondary to be controlled precisely with regard to the coal dust quantity entering the burner. It is imperative for the velocity ratio of the transporting and combustion air to be optimal.

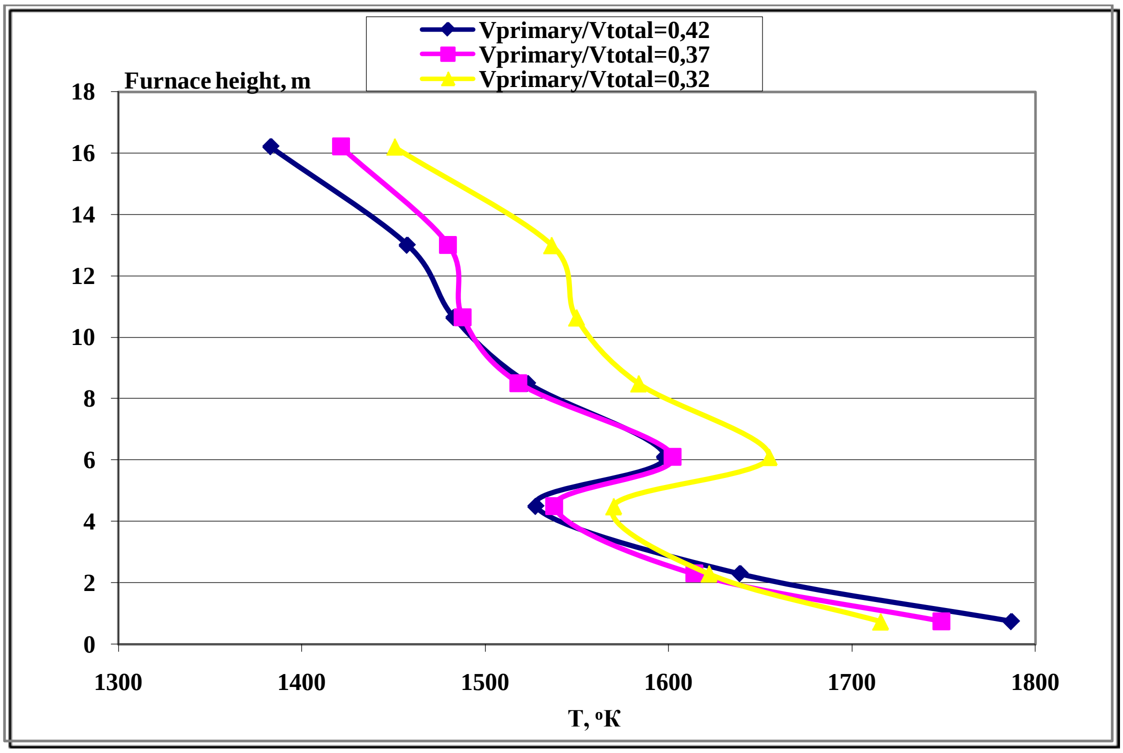


Fig.10 Temperature variations along combustion chamber height at different $V_{primary}/V_{total}$ ratio

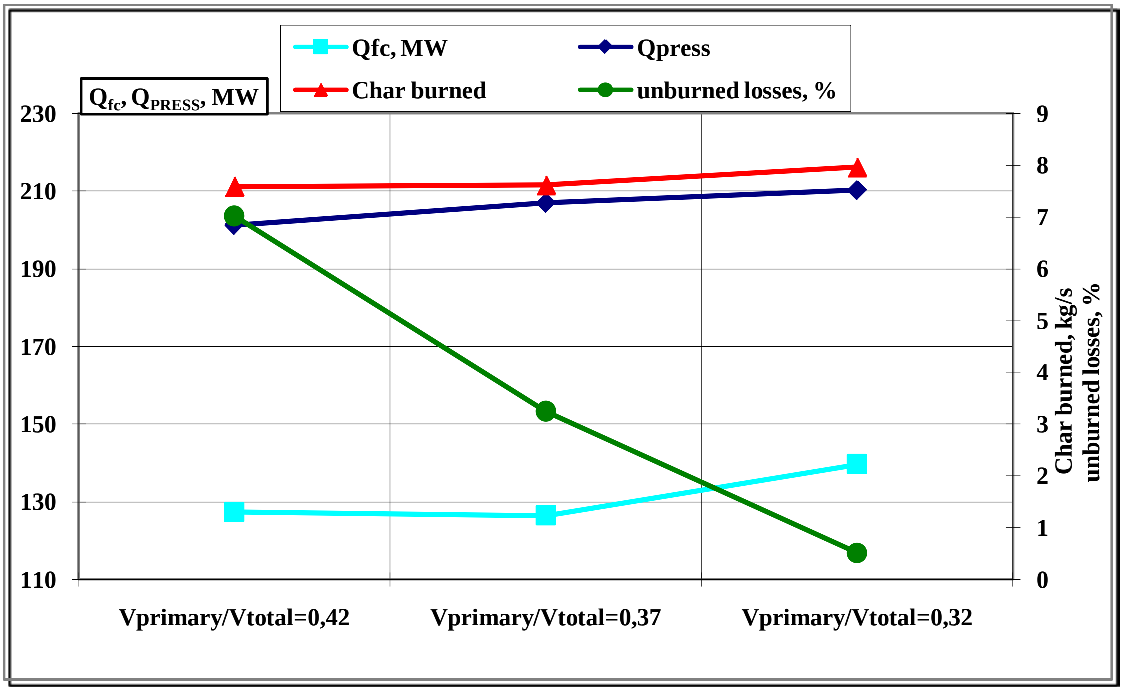


Fig.11 Variations of parameters characterizing furnace operation at different $V_{primary}/V_{total}$ ratio

4.3. Group III model investigations

4.3.1. Initial conditions with additional over-fire system

An investigation of the possibility for boiler No 4 at TPP "Ruse East" to generate less nitrogen oxides through burner modification is performed - more specifically by installing additional over-fire system along the furnace height.

Using the created model few small adjustments to the current state are executed including:

1. On the outlet of the smelter five additional openings on both burner sides are installed;
2. The openings have rectangular shape with dimensions *0,75 m x 0,45 m* through which the tertiary air is supplied;
3. Figure 12 presents the design of the modified combustion chamber.

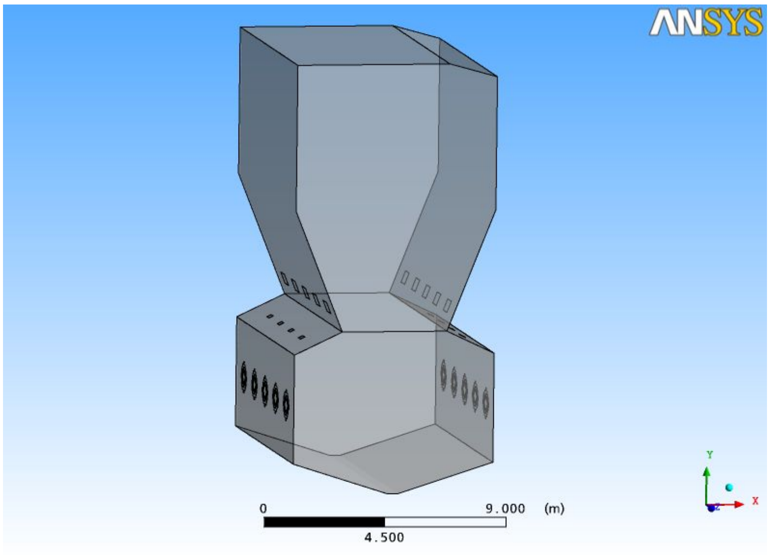


Fig.12 Furnace design view in ANSYS CFX

The modified design of the combustion chamber of boiler No 4 was a subject of numerous investigations. The following three cases are considered:

- Case 3.1 – The total amount of organized air supply is $V_{air} = 385\,000\ Nm^3/h$ and the distribution is: *11 %* as drying and transporting agent to vapor burners, *39 %* as primary and *48 %* as secondary air. No tertiary air is fed to the furnace;

♦ Case 3.2 – The total amount of organized air supply is $V_{air} = 385\,000\ Nm^3/h$ and the distribution is: *11 %* as drying and transporting agent to vapor burners, *39 %* as primary and *30 %* as secondary air. Tertiary air *18 %* and the remaining *2 %* are fed to vapor burners;

♦ Case 3.3 – The total amount of organized air supply is $V_{air} = 317\,000\ Nm^3 / h$ and the distribution is: *11 %* as drying and transporting agent to vapor burners, *30 %* as primary and *30 %* as secondary air. Tertiary air *27 %* and the remaining *2 %* are fed to vapor burners.

The following parameters are the same for all cases above:

- Organized air supply flow, $V_{air} = 385\,000\ Nm^3\ /\ h;$
- Coal consumption, $B = 42,5\ t/h$;
- Average coal fineness in main burners - *57* μm*;*
- Average coal fineness in vapor burners - *31* μm*;*
- Air flow for coal dust drying and transportation to vapor burners is *11 %* of the total organized air supply.

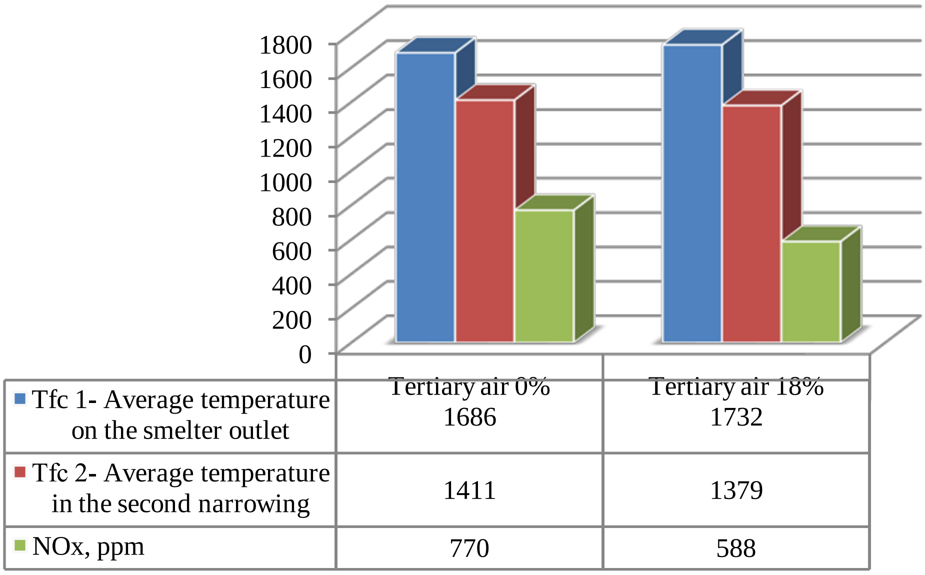
4.3.2. Group III results from model investigations

Figure 13 illustrates some of the results for Case 3.1 and Case 3.2 the analysis of which can be summarized in:

1. The useful heat in the smelter is approximately the same – *133 MW* without tertiary air and *130 MW* with tertiary air;
2. In the case where tertiary air is fed to the boiler the temperature on the smelter outlet is slightly higher (*1732 °K*) than the case without tertiary air (*1686 °K*);
3. There is a difference in the amount of heat in the flue gas on the furnace outlet (*13 MW* more when no tertiary air is available) due to a char portion not fully burned when tertiary air is available (*0,441 kg/s* less burned char);
4. As expected when the over-fire system is operational the concentration of NO_x decreases (from *770 ppm with tertiary air* down to *588 ppm without tertiary air*). This is a *24 %* difference when portion of the secondary air is fed as tertiary – above the smelter. In conclusion for these 2 cases less efficient combustion leads to reduction of the nitrogen oxides concentration. The result is absolutely reasonable and correlates to numerous investigations.

4.3.3. Comparative analysis between Case 3.2 and Case 3.3

This analysis is an additional inquiry for measures that can provide even greater reduction of the NO_x concentration: increased tertiary air flow - to *18 %* for Case 3.2 and *27 %* for Case 3.3. Furthermore a partial redistribution of the total amount organized air supply is present as the secondary air flow remains the same but the primary air is reduced on account of the tertiary one.



	Tertiary air 0%	Tertiary air 18%
🟦 Tfc 1- Average temperature on the smelter outlet	1686	1732
🟥 Tfc 2- Average temperature in the second narrowing	1411	1379
🟩 NOx, ppm	770	588

Fig.13 Parameters variations when portion of the secondary air is fed as tertiary

Some of the acquired results are shown in Figure 14 and the conclusions are as follow:

1. The useful heat in the smelter increases with higher tertiary air flow (from *130,1 MW* to *142,5 MW*). This is due to the decreased primary air flow;
2. In the case where the tertiary air flow is higher the temperature on the smelter outlet is higher (from *1732 °K* to *1785 °K)*;
3. There is a difference in the amount of heat in the flue gas on the furnace outlet but in this case not very significant – *6,4 MW*;
4. Increasing the tertiary air from *18 %* to *27 %* increases the unburned fuel by *0,069 kg/s* meaning there isn't a difference to the unburned fuel losses;
5. By increasing the tertiary air the concentration of NO_x decreases even further – from *588 ppm* down to *499 ppm*. This is additional *15 %* reduction and compared to the *770 ppm* in previous cases it is a total reduction of *35 %*.

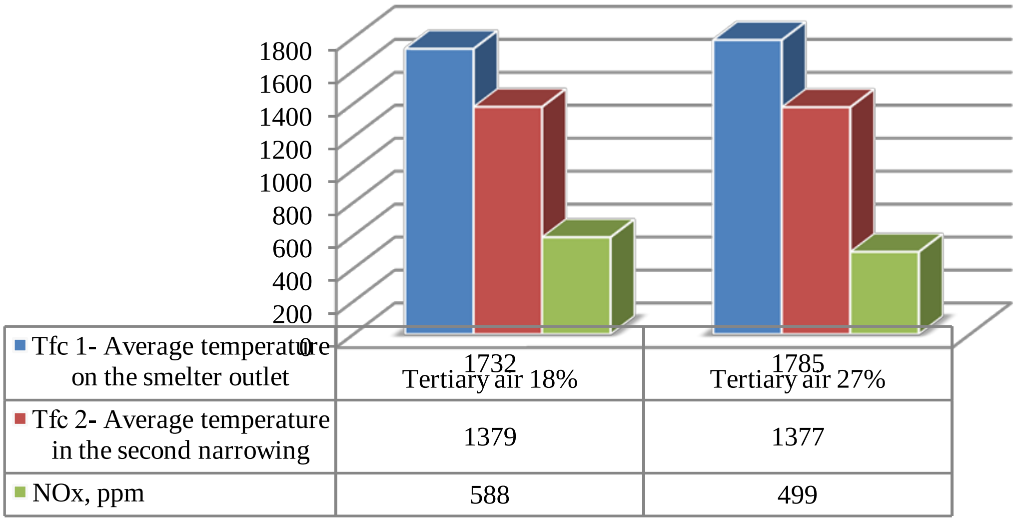


Fig.14 Parameter variations with increased tertiary air share

Figure 15 represents the variations of NO_x concentration for the three cases.

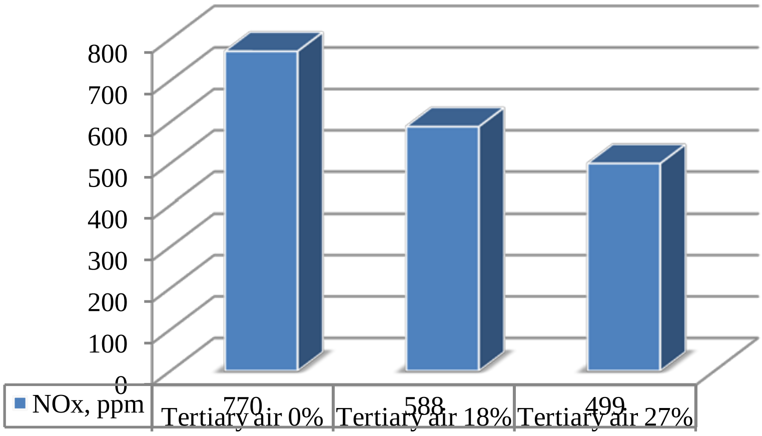


Fig.15 NO_x concentration on the furnace outlet at different amount tertiary air

5. Conclusions

Summarizing the obtained results from the conducted studies the following conclusions can be drawn:

1. An adequate 3D model of the combustion chamber operation for boiler type 1B-365-139 is prepared and validated using operational and design data;

2. Three different groups of investigations are performed relying on the 3D model that is in good agreement with the operational and design data – at different quantities organized air supply, different primary/total air ratio and with an over-fire system;

3. The results apply strictly for the boiler subject to the studies but generally accepted conclusions in this field are confirmed. An example is the conclusion that the introduction of over-fire system reduces the nitrogen oxides by 30÷50 %. In this case 35 % reduction is achieved.

This paper presents the results from simulation investigations that are partly implemented to the operation of boiler No 4 at TPP “Ruse East”.

Group III studies can serve as a basis for comparison and assessment of subsequent modification of the combustion chamber of this boiler type for further reduction of the generated nitrogen oxides.

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