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MINIMIZATION OF TOXIC EMISSIONS DURING BURNING LOW-GRADE FUEL AT KAZAKHSTAN THERMAL POWER PLANT

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Abstract. This paper presents new results of computational experiments on the implementation of Overfire Air (OFA) technologies using an example of a combustion chamber of the BKZ-75 boiler of the Shakhtinskaya power plant (Shakhtinsk, Kazakhstan) burning high-ash Karaganda coal. The effect of mass air flow through special nozzles located above the burner level on the flow aerodynamics, temperature fields, concentration fields of carbon monoxide CO and nitrogen NO over the entire volume of the combustion chamber was studied. The studied characteristics were compared for various percentages of supplying additional air through OFA injectors: OFA is 0 % (basic version), 10 % and 18 %. It was shown that the installation of OFA injectors leads to a change in the field of the total velocity vector, temperature, and concentrations of carbon oxides and nitrogen. An increase in the percentage of air supplied through OFA injectors to 18 % leads to a decrease in the concentrations of carbon monoxide CO by about 36 % and nitrogen oxide NO by 25 % compared with the base case. The obtained results will optimize the process of burning pulverized fuel in the combustion chamber of the BKZ-75 boiler, increase the efficiency of fuel burnout, reduce harmful emissions and introduce OFA-technology at other coal-burning thermal power plants.

Keywords: Heat and mass transfer, combustion, numerical simulation, stepwise combustion (OFA), aerodynamics, temperature, carbon oxides and nitrogen.

1. Introduction

In most economically developed countries of the world, as in Kazakhstan, a significant amount of thermal and electric energy is generated at thermal power plants (TPPs) burning organic fuel. The main fuel for Kazakhstan's TPPs is coal, which has a significant moisture content and relatively low calorific value, as well as a high content of ash (more than 40 %) and sulfur [1–6]. Given the large amount of cheap Kazakh coal and a complex of large coal-fired power plants over the next two decades, it is expected that the Republic will rely heavily on coal fuel [7–10].

The use of low-grade fuel with high ash content places high demands on the reliability of the boiler plants of TPPs, as well as on ensuring strict environmental requirements for the emissions of carbon monoxide CO and nitrogen NO [11–15]. Currently, the share of emissions from sources of the energy complex of Kazakhstan with its high dependence on coal as the main source of energy is 43.7 % of all emissions of pollutants into the air in Central Asia. For this purpose, the development and implementation of environmentally friendly technologies for the combustion of solid fuels in the furnaces of boilers of Kazakhstan TPPs are relevant [16–20].

At present, a large number of measures have been developed and implemented to tighten the requirements for harmful emissions of thermal power plants, the most dangerous of which are nitrogen oxides. There are various methods for reducing emissions of nitrogen oxides [21–27], the most appropriate of which is the introduction of technology for suppressing nitrogen oxides at the stage of the fuel combustion in the combustion chamber. Stepwise fuel combustion - Overfire Air (OFA) technology is one of the most effective methods to reduce the concentration of nitrogen oxides NOx [28, 29].

The stepwise air supply to the combustion chamber with OFA- technology consists in supplying the required amount of air for the burning coal as follows: 70-90 % air is supplied to the burners and 10-30 % through the OFA injectors located above the burners. In this case, a low-temperature oxygen-depleted and fuel-rich combustion zone is created in the lower part of the combustion burner, which reduces the formation of NOx from fuel nitrogen (fuel NOx). At the same time, the low temperature in the oxygen enriched zone of OFA injectors minimizes the formation of NOx from the air (thermal NOx) [30, 31].

The reconstruction of Kazakhstan TPPs, testing of commissioning works by means of industrial tests with the implementation of the Overfire Air (OFA) technology described above have significant limitations due to the high complexity and high cost. In this regard, the main methods for studying the processes occurring in the combustion chambers of thermal power plants are numerical modeling methods and the implementation of computational experiments based on them that adequately reflect the real physical processes occurring in the combustion chambers [32–39].

The purpose of this work is to introduce Overfire Air technologies using the latest information technologies and 3D computer simulation methods using the example of the combustion chamber of the BKZ-75 boiler of the Shakhtinskaya TPP. This will optimize the processes that occur during the burning of high-ash energy fuel, reduce harmful dust and gas emissions into the atmosphere and create and implement a way to produce a "clean" energy at other coal-fired TPPs in the future.

2. Object of study

For conducting numerical experiments on the implementation of OFA technologies, the combustion chamber of the BKZ-75 boiler of the Shakhtinskaya TPP (Shakhtinsk, Kazakhstan) was selected. Boiler BKZ-75 has a height of 16.75 m, a depth of 6.6 m, a width of 6 m, a vertical water-tube structure; it has a U-shaped scheme for the movement of the working medium, based on natural circulation through the drum. The boiler is equipped with four pulverized coal burners which are installed in two on the front and back walls in one tier. The boiler BKZ-75 of the Shakhtinskaya THP plant uses the dust of the Karaganda coal grade KR-200 with ash-content of 35.1 %, volatile yield of 22 %, humidity of 10.6 % and gross calorific value of 18.55 MJ/kg. The boiler is equipped with four burners installed, two burners from the front and from the rear in one tier at a height of $z = 4$ m, and four OFA injectors at a height of $z = 9.4$ m. A more detailed description of the boiler's combustion chamber, mathematical model, solution method and the application software package is given in the following works [40–48]. General view of the combustion chamber of the BKZ-75 boiler, the layout of the burners and OFA injectors are shown in Figure 1. For numerical simulation, a finite-difference grid was selected (Figure 1a), which is 455 040 control volumes.

Various percentages of supplying additional air through OFA injectors were investigated: OFA = 0 % (basic version), OFA = 10 %, OFA = 18 %. Flow aerodynamics (distribution of the overal velocity vector), temperature fields, concentration fields of carbon monoxide CO and nitrogen oxide NO over the entire volume of the combustion chamber were obtained, and a comparative analysis was performed for the studied modes.

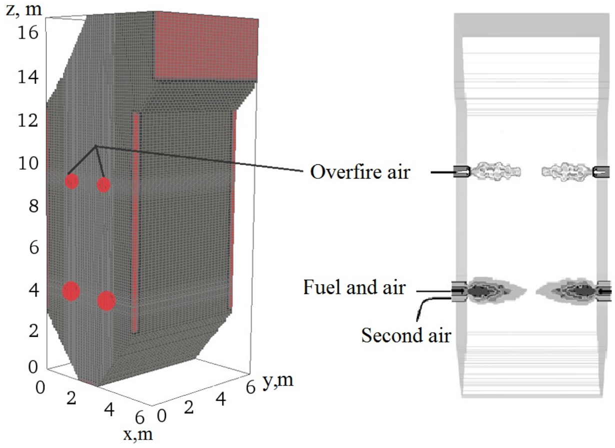

Figure 1. General view of the combustion chamber of the BKZ-75 boiler of the Shakhtinskaya TPP, a) its breakdown into control volumes and b) the layout of OFA burners and injectors.

3. Results

Figures 2 and 3 show the distribution of the overal velocity vector in the region of the location of the burners ($z = 4$ m) and OFA injectors ($z = 9.4$ m) for the base case (OFA = 0 %) and using the Overfire Air technology (OFA = 18 %). An analysis of the figures shows that for these two investigated percentages of air supply through OFA nozzles, the torch core is located in the centre of the combustion chamber and is determined by the region of the collision of flows from the burners.

Figure 4 shows the temperature distribution in the area of the burners for the base case (OFA = 0 %) and using the technology of Overfire Air (OFA = 10 %, OFA = 18 %). An analysis of Figure 4 shows that with an increase in the volume of the air supplied through the injectors OFA, the temperature in the centre of the combustion chamber increases: for OFA = 0 % $t_{cc.ch.}$ = 620.6 °C; OFA = 10 % $t_{cc.ch.}$ = 750.3 °C;OFA = 18 % $t_{cc.ch.}$ = 744.1 °C. This is due to the fact that with the OFA, the area around the burners is depleted in oxygen, which leads to a decrease in the coefficient of excess air. On the contrary, more air is supplied in the area of the location of OFA injectors, chemical reactions occur more intensively and the temperature rises: for OFA = 0 % $t_{cc.ch.}$ = 987.31 °C; OFA = 10 % $t_{cc.ch.}$ = 918.56 °C; OFA = 18 % $t_{cc.ch.}$ = 879.17 °C (Figure 5).

This temperature behaviour is clearly seen in the Figure 6, where the temperature distribution T over the height of the boiler combustion BKZ-75 is presented for various percentages of air supplied through OFA injectors. At the outlet of the combustion chamber, we have a further decrease in temperature: OFA = 0 % – 885.80 °C; OFA = 10 % – 865.91 °C; OFA = 18 % – 856.27 °C. The temperature at the

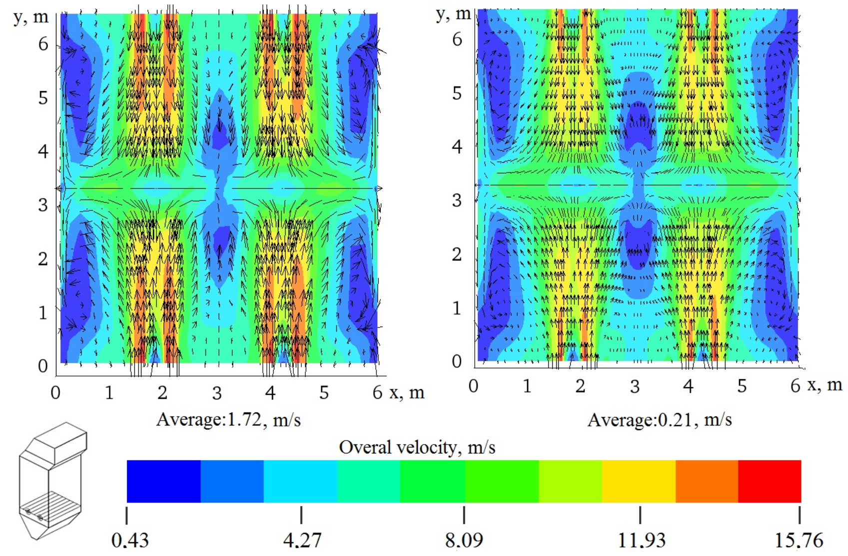

Figure 2. The field of the overal velocity vector in the area of the arrangement of the burners for various percentages of air supplied through the injectors: a) OFA = 0 % (basic version), b) OFA = 10 %.

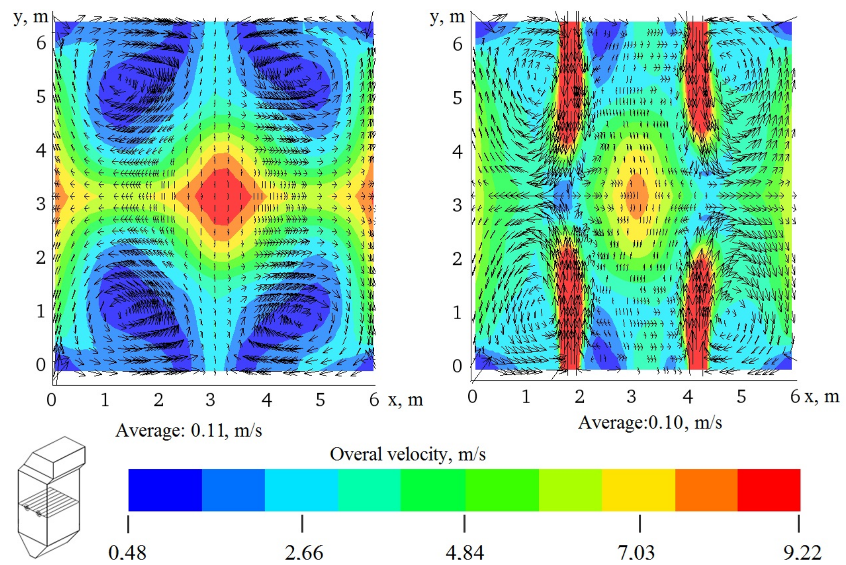

Figure 3. The field of the overal velocity vector in the region of the arrangement of OFA injectors for various percentages of air supplied through injectors: a) OFA = 0 % (basic version), b) OFA = 10 %.

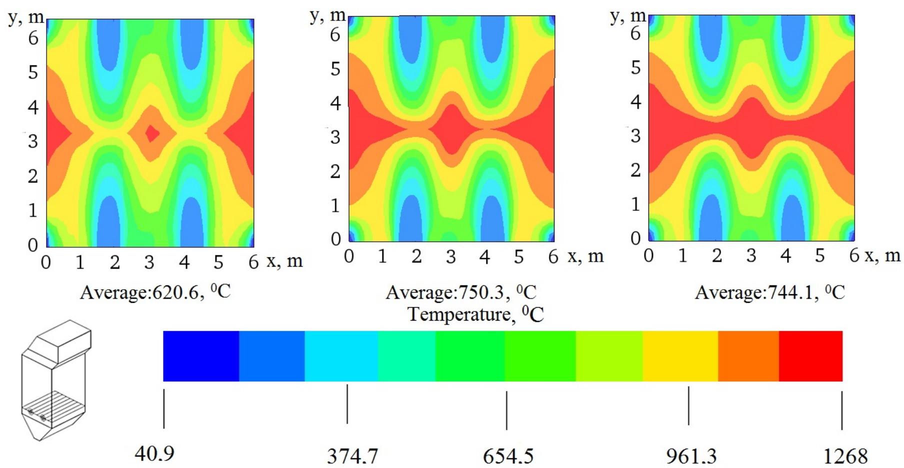

Figure 4. Temperature distribution in the area of burner arrangement for various percentages of air supplied through injectors: a) OFA = 0 % (basic version), b) OFA = 10 %, c) OFA = 18 %.

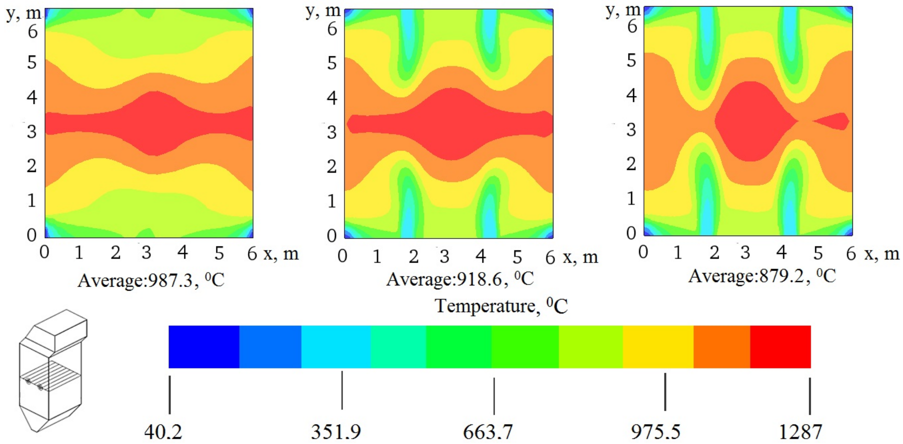

Figure 5. Temperature distribution in the area of the location of OFA injectors for various percentages of air supplied through injectors: a) OFA = 0 % (basic version), b) OFA = 10 %, c) OFA = 18 %.

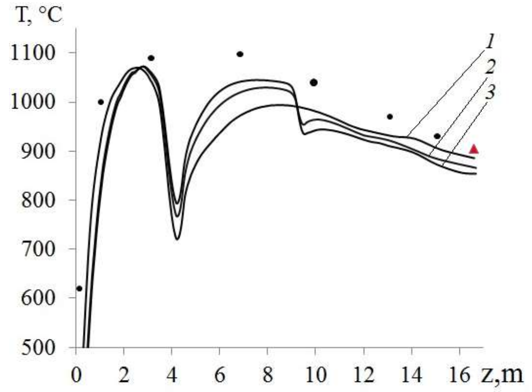

Figure 6. Temperature distribution T along the height of the combustion chamber of the boiler BKZ-75 at various percentages of air supplied through injectors OFA:1 – OFA = 0 % (basic version), 2 – OFA = 10 %, OFA = 18 %; "black circle" - experiment at TPP [49]; "red triangle" – is theoretical values obtained by the method of thermal calculation CBTI – Central Boiler-and-Turbine Institute [50].

outlet of the combustion chamber is confirmed by experimental data directly at the TPP [49] and its theoretical value calculated by the CBTI method for the base case [50].

Figures 7 and 8 below illustrate two-dimensional distributions of the concentration of carbon monoxide CO in the area of the arrangement of burners and OFA injectors for three options for supplying additional air: a) OFA = 0 % (basic version), b) OFA = 10 %, c) OFA = 18 %.

It can be noted that carbon monoxide is concentrated mainly in the zone of the main distribution of the fuel flow and oxidizer (air) from the burners, i.e. where there is a large amount of carbon fuel. With an increase in the volume of air supplied through OFA injectors, further oxidation of carbon monoxide CO to carbon dioxide CO_2 occurs, which leads to a decrease in CO in the exhaust gases and at the outlet from the combustion space (Figure 9). Analysis of the figure shows that an increase in the volume of air supplied through OFA injectors allows to reduce the concentration of carbon monoxide CO at the outlet of the combustion chamber from $7.3 \cdot 10^{-4}$ kg/kg to $4.6 \cdot 10^{-4}$ kg/kg, which is about 36 %.

Distributions of nitrogen oxide NO concentration along the height of the combustion chamber, in the area of the arrangement of burners and OFA injectors and for three options for supplying additional air through injectors: a) OFA = 0 % (basic version), b) OFA = 10 %, c) OFA = 18 % are presented in Figures 10, 11 and 12. It is shown that an increase in the volume of the air supplied through the injectors reduces the concentration of nitrogen oxides NO at the outlet of the furnace space. So at OFA = 18 %, the concentration of nitrogen oxide NO at the outlet of the combustion chamber is 277.12 mg/nm^3, which is about 25 % lower than in the base case, where the concentration of nitrogen oxide is 368.08 mg/nm^3.

The maximum permissible concentration for nitrogen oxides NO, adopted in the Republic of Kazakhstan, is 850 mg/nm^3. Thus, we can conclude that the introduction of OFA technology on the BKZ-75 boiler of the Shakhtinskaya TPP allows to significantly reduce emissions of harmful substances (carbon oxides CO and nitrogen NO) and extend the results to the implementation of this technology on other coal-fired TPPs.

4. Conclusions

Computational experiments have been performed to study the characteristics of heat and mass transfer (flow aerodynamics, temperature and concentration fields) with the introduction of the OFA technology in the combustion chamber of the BKZ-75 boiler of the Shakhtinskaya TPP burning high-ash karaganda coal. The effect of various percentages of supplying additional air through the injectors was studied: OFA is 0 % (basic version), 10 % and 18 %.

It was shown that the installation of additional nozzles for air above the level of the burners leads to

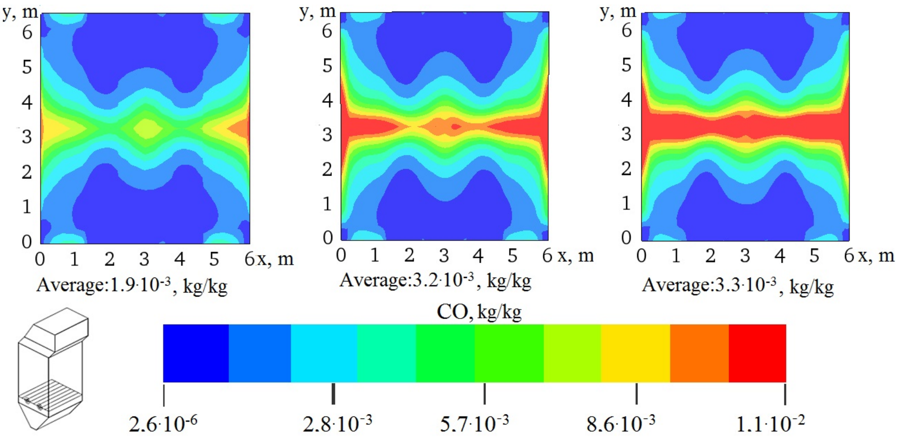

Figure 7. The distribution of the concentration of carbon monoxide CO in the area of the location of the burners for different volumes of air supplied through the injectors: a) OFA = 0 % (basic version), b) OFA = 10 %, c) OFA = 18 %.

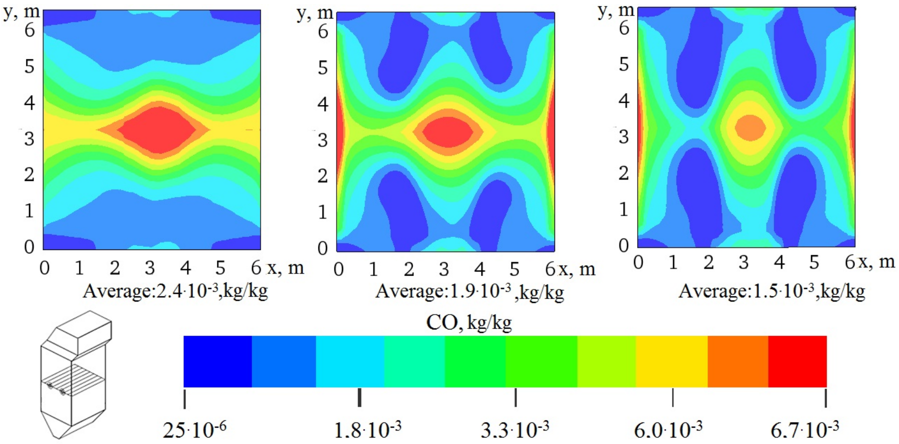

Figure 8. The distribution of the concentration of carbon monoxide CO in the area of the location of OFA injectors at various percentages of air supplied through injectors: a) OFA = 0 % (basic version), b) OFA = 10 %, c) OFA = 18 %.

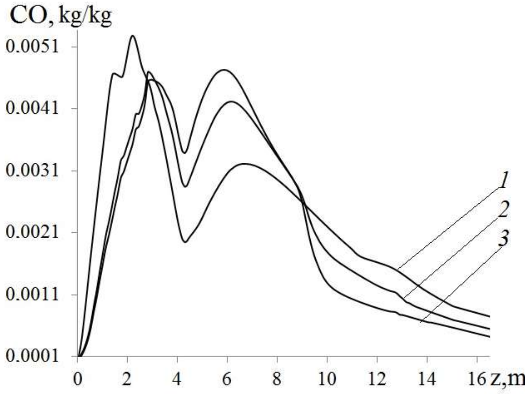

Figure 9. The distribution of the concentration of carbon monoxide CO at the outlet of the combustion chamber of the boiler BKZ-75 at various percentages of air supplied through OFA injectors: a) OFA = 0 % (basic version), b) OFA = 10 %, c) OFA = 18 %.

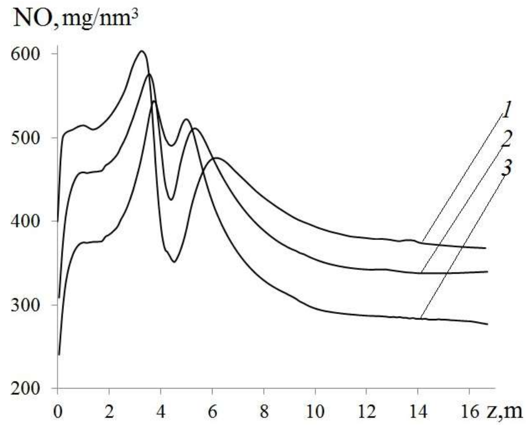

Figure 10. Distribution of the concentration of nitrogen oxide NO along the height of the combustion chamber of the BKZ-75 boiler at various percentages of air supplied through OFA injectors: a) OFA = 0 % (basic version), b) OFA = 10 %, c) OFA = 18 %.

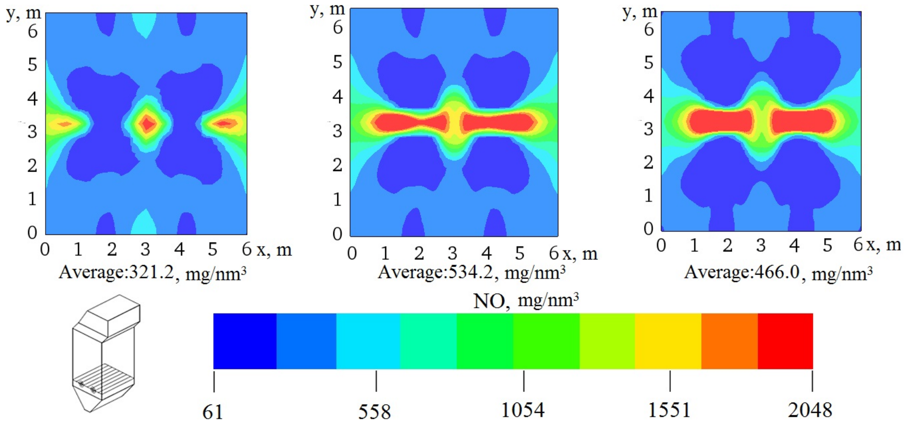

Figure 11. The distribution of the concentration of nitrogen oxide NO in the area of the burners for different volumes of air supplied through OFA injectors: a) OFA = 0 % (basic version), b) OFA = 10 %, c) OFA = 18 %.

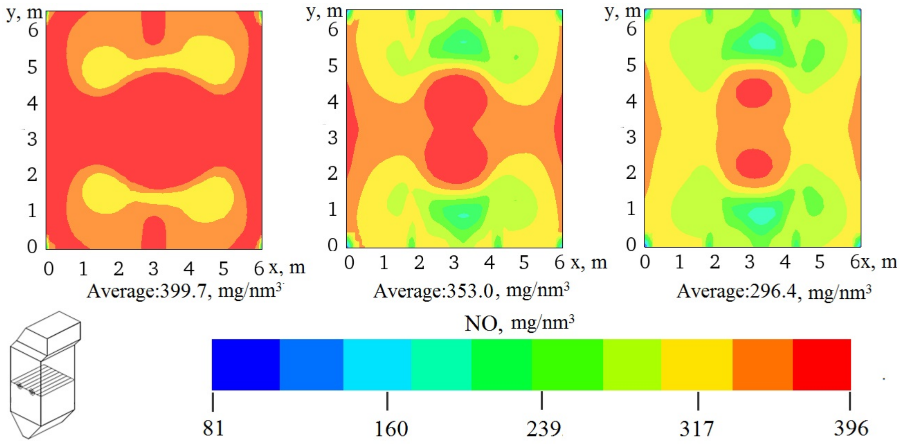

Figure 12. The distribution of the concentration of nitrogen oxide NO in the area of OFA injectors at various percentages of air supplied through injectors: a) OFA = 0 % (basic version), b) OFA = 10 %, c) OFA = 18 %.

a change in the overal velocity vector, temperature T, and the concentration of carbon oxides CO and nitrogen NO over the entire volume of the combustion chamber and at its exit.

As the percentage of air supplied through the OFA nozzles increases, the temperature in the region of the belt zone of the burners of the combustion chamber increases. This is due to the fact that, in this case, the area of the burners is depleted in oxygen, which leads to a decrease in the coefficient of excess air. On the contrary, in the area of the location of OFA injectors, the temperature decreases.

It was shown that an increase in the percentage of air supplied through OFA injectors to 18 % leads to a decrease in the concentrations of carbon oxide CO by about 36 % and nitrogen oxide NO by 25 % when compared with the base case.

The results of computational experiments on the combustion of pulverized coal in the combustion chamber of the BKZ-75 boiler were compared with experimental data obtained in the course of field experiments conducted directly at the operating Shakhtinskaya TPP and with a theoretical temperature value calculated by the CBTI method for the basic version.

The results will optimize the combustion of low-grade fuel in the combustion chamber of the BKZ-75 boiler, increase the efficiency of fuel burnout, reduce harmful emissions and introduce OFA technology at other coal-burning thermal power plants.

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