Staged supply of fuel and air to the combustion chamber to reduce emissions of harmful substances

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Introduction

Innovative solutions are transforming the energy system and opening up new opportunities for a decarbonized future. Around the world, inefficient coal thermal power plants began to close. But this trend is not universal. Coal is very unevenly distributed across the planet. There is a lot of coal, so countries that have coal deposits continue to use it. Leading countries are declaring they will achieve carbon neutrality by 2060, but the pace of coal production is not going to slow down due to high natural gas prices and huge demand for electricity around the world.

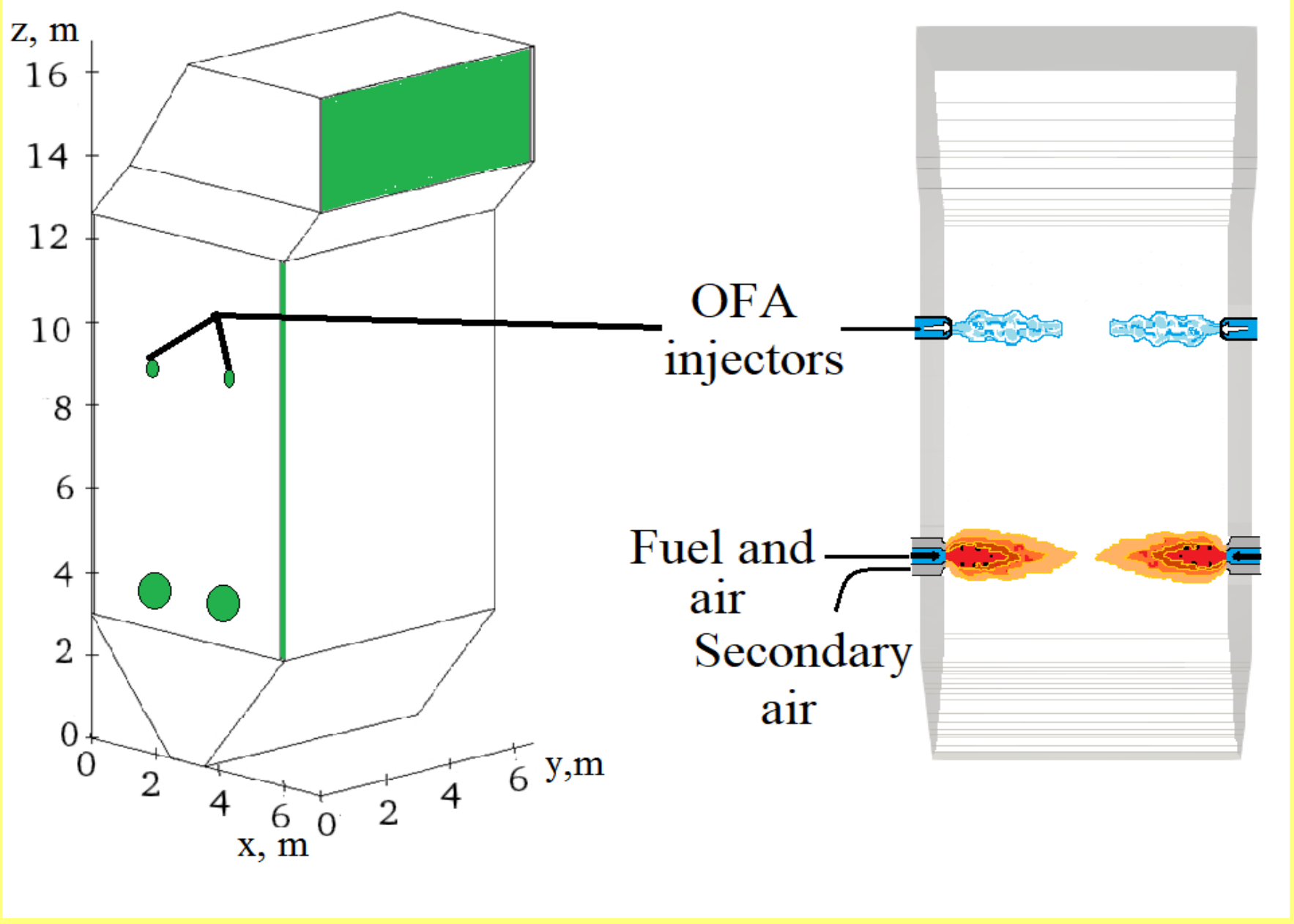
Currently, many methods are used to minimize harmful dust and gas emissions at coal-fired thermal power plants, the main of which are: changing the combustion technology and cleaning gases after combustion. Changes in combustion technology include: the use of modified burners, afterburning of fuel, recirculation of exhaust gases, preparation of coal for combustion, etc. Practice has shown that a significant means of suppressing nitrogen oxides, especially in pulverized coal-fired boilers, is the technology of two-stage fuel combustion.

Two-stage combustion of fuel - air supply to the burner devices in two stages in the first stage of a smaller part of the air and in the second - a larger one. In the first stage at $\alpha_T < 1$ fuel is gasified by incomplete combustion. It is associated with a decrease in temperature and the production of gaseous fuel. In the second stage, the resulting gas burns at $\alpha_T > 1$, which leads to a significant decrease in the yield of nitrogen oxides.

In the study of heat and mass transfer processes in combustion chambers with the aim of developing environmentally friendly coal technologies, the role of numerical methods and computational experiments is growing. Their use makes it possible to achieve a geometric and physical similarity of the objects under study, compliance with all the main parameters and regime conditions that are adequate to the technological scheme of fuel combustion at a real power facility [1-2].

The object of calculations

Figure 1 shows a general view of the combustion chamber of the BKZ-75 boiler (Figure 1a) and the layout of burners and injectors for the introduction of two-stage fuel combustion technology (Figure 1b). The finite difference grid has steps along the X, Y, Z axes: 90×32×158, which is 455040 control volumes.



a) b)

Figure 1. General view of the combustion chamber of the BKZ-75 boiler a), and its layout of burners and OFA-injectors b)

To implement the technology of two-stage fuel combustion, various modes of additional air supply through OFA injectors were chosen: OFA is 0% (basic version, traditional combustion), 5%, 10%, 15%, 18%, 20%, 25% and 30% of the total air volume is supplied through the injectors at the top of the combustion chamber. Table 1 shows the calculated flow rates and velocities of the secondary air supplied through the OFA injectors for the above modes.

Table 1. Technical characteristics of the BKZ-75 boiler

Characteristic	Value
Number of OFA injectors, pcs.	4
Height of location of burners h (z), m	4
Altitude of the tier of OFA-injectors h (z), m	9,4
OFA injector diameter, m	0,325

Modeling of coal combustion

In this work, to study heat and mass transfer in high-temperature media with physical and chemical processes, physical, mathematical and chemical models of the problem are used, which include the equations for the balance of mass, momentum, concentrations of gas components and energy. These equations take into account the no isothermal and turbulent flow, the multiphase nature of the medium, chemical reactions, and radiant heat transfer. In a generalized form, they can be written as [3-4]:

$$\frac{\partial(\rho\phi)}{\partial t} = -\frac{\partial(\rho u_1\phi)}{\partial x_1} - \frac{\partial(\rho u_2\phi)}{\partial x_2} - \frac{\partial(\rho u_3\phi)}{\partial x_3} + \frac{\partial}{\partial x_1}\left[\Gamma_\phi \frac{\partial\phi}{\partial x_1}\right] +$$

$$+ \frac{\partial}{\partial x_2}\left[\Gamma_\phi \frac{\partial\phi}{\partial x_2}\right] + \frac{\partial}{\partial x_3}\left[\Gamma_\phi \frac{\partial\phi}{\partial x_3}\right] + S_\phi$$

where ϕ - transport variable (mass, momentum, energy, concentration of components, kinetic energy of turbulence and its dissipation). Γ_ϕ– exchange ratio, S_ϕ – source term, which is determined by the chemical kinetics of the process, nonlinear effects of thermal radiation, interfacial interaction, as well as the multi-stage nature of chemical reactions.

The system of equations (1), which is solved numerically using the control volume method, was subsequently successfully used in computational experiments on the combustion of high-ash coal at Kazakh thermal power plants. The control volume method is often used in 3D modeling of turbulent flows with physical and chemical transformations that take place during fuel combustion in combustion chambers. This method is quite simple, clear and stable, does not require huge computational costs and is used in solving many technical problems.

The standard *k*-ε model was used in the work, where *k* is the kinetic energy of turbulence, ε is its dissipation. In this model, the quantities k and ε are determined by the following system of equations [3-4]:

$$\frac{\partial(\overline{\rho}k)}{\partial t} = -\frac{\partial\left(\overline{\rho}\,\overline{u}_j k\right)}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\frac{\mu_{eff}}{\sigma_k}\frac{\partial k}{\partial x_j}\right] + P - \overline{\rho}\cdot\varepsilon$$

$$\frac{\partial(\overline{\rho}\varepsilon)}{\partial t} = -\frac{\partial\left(\overline{\rho}\,\overline{u}_j \varepsilon\right)}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\frac{\mu_{eff}}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right] + C_{\varepsilon,1}\cdot\frac{\varepsilon}{k}\cdot P - C_{\varepsilon,2}\cdot\frac{\varepsilon^2}{k}\cdot\overline{\rho}$$

Result

As a result of the numerical experiments on the introduction of two-stage combustion of high-ash Karaganda coal, an aerodynamic flow pattern (distribution of the full velocity vector), temperature and concentration fields of carbon monoxide CO and nitrogen dioxide NO_2 were obtained throughout the entire volume of the combustion chamber and at the exit from it. A comparative analysis of the main characteristics of the process of heat and mass transfer in the combustion chamber for the studied modes of supplying additional air through the injectors was carried out.

Figure 2 shows the dependences of the temperature T, concentrations of carbon monoxide CO and nitrogen dioxide NO_2 at the outlet of the combustion chamber on various modes of air supply through the injectors: OFA is 0% (base case), 5%, 10%, 15%, 18% , 20%, 25% and 30% of the total volume of air required for fuel combustion.

Analyzing the results of the studied regimes (Figure 2), one can notice a decrease in temperature T (curve 1), concentrations of nitrogen dioxide NO_2 (curve 2) and carbon monoxide CO (curve 3) in the furnace space as the volume of additional air through OFA injectors increases. As for nitrogen dioxide (curve 2), we see that when introducing the technology of two-stage fuel combustion, the best option for reducing (by almost 25%) the concentration of NO_2 at the outlet of the combustion chamber is to use injectors with OFA=18%. A further increase in the volume of additional air leads to an increase in the concentration of nitrogen dioxide NO_2 at the outlet of the furnace.

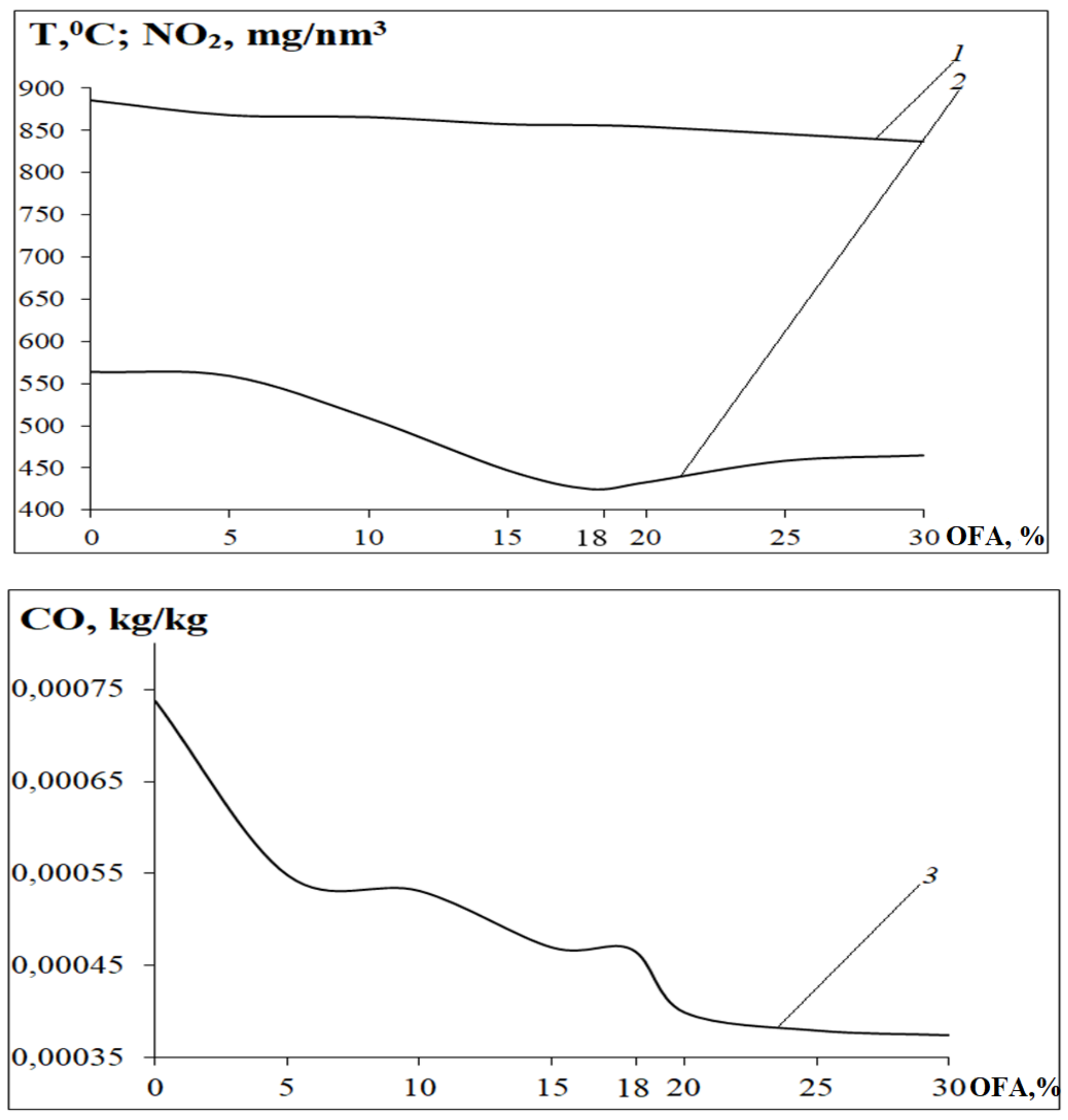


Figure 2. Dependence of temperature T, concentrations of carbon monoxide CO and nitrogen dioxide NO_2 at the outlet of the combustion chamber on the volume of additional air through OFA injectors: curve 1 - T; curve 2 - CO; curve 3 - NO_2

Conclusions

Based on the results of the research, we formulate the following conclusions:

- To carry out computational experiments, physical-mathematical, chemical and geometric models have been developed that adequately reflect the real technological processes of low-grade coal combustion in the combustion chamber of the BKZ-75 boiler at Shakhtinskaya TPP.
- Computational experiments were carried out to introduce the technology of two-stage fuel combustion under various modes of additional air supply through OFA-injectors: 0% (basic version, traditional combustion), 5%, 10%, 15%, 18%, 20%, 25% and 30 % of the required total air volume.
- It is shown that an increase in the volume of additional air leads to an increase in temperature in the center of the combustion chamber and to its decrease in the area of the OFA injectors. As we move towards the exit from the furnace, the temperature field becomes even, and the differences in temperature values for different modes of additional air supply through the injectors decrease.
- It has been shown that the use of two-stage combustion technology in the combustion chamber of a coal-fired TPP leads to a significant reduction in emissions of carbon monoxide CO and nitrogen dioxide NO_2 from the combustion space. An increase in the percentage of air supplied through the injectors to 18% leads to a decrease in the concentrations at the outlet of the combustion chamber of carbon monoxide CO by about 36%, and nitrogen dioxide NO_2 by 25% compared to the base case.
- On the example of the BKZ-75 boiler at the Shakhtinskaya TPP, the possibility and efficiency of using staged combustion at other real heat and power coal facilities is shown. This will optimize the process of burning coal fuel and solve environmental problems of minimizing harmful emissions into the environment.

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