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REDUCING EMISSIONS OF HARMFUL SUBSTANCES AT COAL-HEATED THERMAL POWER PLANTS

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Abstract. In this research, using the three-dimensional modeling method, computational experiments were carried out to introduce two-stage combustion technology inviting the example of the combustion chamber of the BKZ-75 boiler at the Shakhtinskaya TPP, burning high-ash Karaganda coal. Computational experiments were carried out on the implementation of two-stage fuel combustion technology under various modes of supplying additional air through OFA injectors: 0% (basic version, traditional combustion), 5%, 10%, 15%, 18%, 20%, 25% and 30% from the required total air volume. It has been shown that the technology of two-stage fuel combustion allows optimizing the process, improving ignition and combustion conditions and minimizing emissions of harmful substances.

Keywords: thermal power plant, two-stage combustion, computational experiment, high-ash coal, temperature, nitrogen oxides

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СОКРАЩЕНИЕ ВЫБРОСОВ ВРЕДНЫХ ВЕЩЕСТВ НА УГОЛЬНЫХ ТЕПЛОВЫХ ЭЛЕКТРИЧЕСКИХ СТАНЦИЯХ

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Аннотация. С использованием метода трехмерного моделирования в данном исследовании были выполнены вычислительные эксперименты по внедрению технологии двухступенчатого сжигания на примере топочной камеры котла БКЗ-75 Шахтинской ТЭЦ, сжигающей высокозольный карагандинский уголь. Проведены вычислительные эксперименты по внедрению технологии двухступенчатого сжигания топлива при различных режимах подачи дополнительного воздуха через OFA-инжекторы: 0% (базовый вариант, традиционное сжигание), 5%, 10%, 15%, 18%, 20%, 25% и 30% от необходимого общего объема воздуха. Согласно результатам исследования, технология двухступенчатого сжигания топлива позволяет оптимизировать процессы, улучшить условия воспламенения и горения, а также минимизировать выбросы вредных веществ.

Ключевые слова: ТЭЦ, двухступенчатое сжигание, вычислительный эксперимент, высокозольный уголь, температура, оксиды азота

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Introduction

The environmental situation in the world is getting worse every year. According to the World Health Organization, more than 92% of the world's population breathes polluted air. Air pollution is significantly influenced by: industrial production, road congestion with urban transport and low ventilation of populated areas. It is these three factors that contribute to the high level of air pollution in populated areas with pollutants such as nitrogen dioxide, carbon monoxide, sulfur dioxide, formaldehyde, hydrogen sulfide, suspended particles, phenol, ammonia (Georgiev, 2022; Xiang, 2003; Yang, 2017; Zaychenko et al., 2018).

The world's leading countries are seeking to increase the use of renewable energy sources, but the industrial economy remains largely dependent on fossil fuels – coal, oil and gas. Recent events in the world have shown that energy sources such as wind and sun, which are characterized by inconsistency (calm and cold weather), may not be enough to provide the world with electricity and heat. Some countries have begun switching to coal, reviving coal-fired power plants, which could slow the global transition to green energy.

Despite the fact that the leading countries of the world announce their plan for 2020-2060. achieving carbon neutrality, the rate of coal production is not expected to slow down. Mainly due to high prices for natural gas, huge demand for electricity, increased development of energy and industry in China, India and the countries of Southeast Asia. Demand for coal remains flat and is likely to reach record highs this year, driving up global emissions. Production records will be broken by the TOP 3 largest coal producers in the world - China, India and the USA (Figure 1).

Attempts to ensure domestic energy consumption by increasing the volume of coal use in almost all Central Asian countries have led to an aggravation of the environmental situation. In countries rich in natural resources, renewable energy sources are still losing competition to traditional types of generation. In the future, the share of coal-fired stations will decrease, but coal in these countries will remain the main type of fuel for now. In this regard, to increase the efficiency of using traditional fuel, various methods of environmentally friendly and efficient combustion are being developed.

The creation of energy-efficient technologies that make it possible to control the main processes of the formation of harmful dust and gas emissions, and the development of recommendations for their reduction is an urgent task in the thermal power industry. Research in the field of progressive technological processes to improve power plants for burning pulverized coal fuels and the use of alternative methods for burning various types of fuel are currently the most relevant for the entire energy complex of the Republic of Kazakhstan.

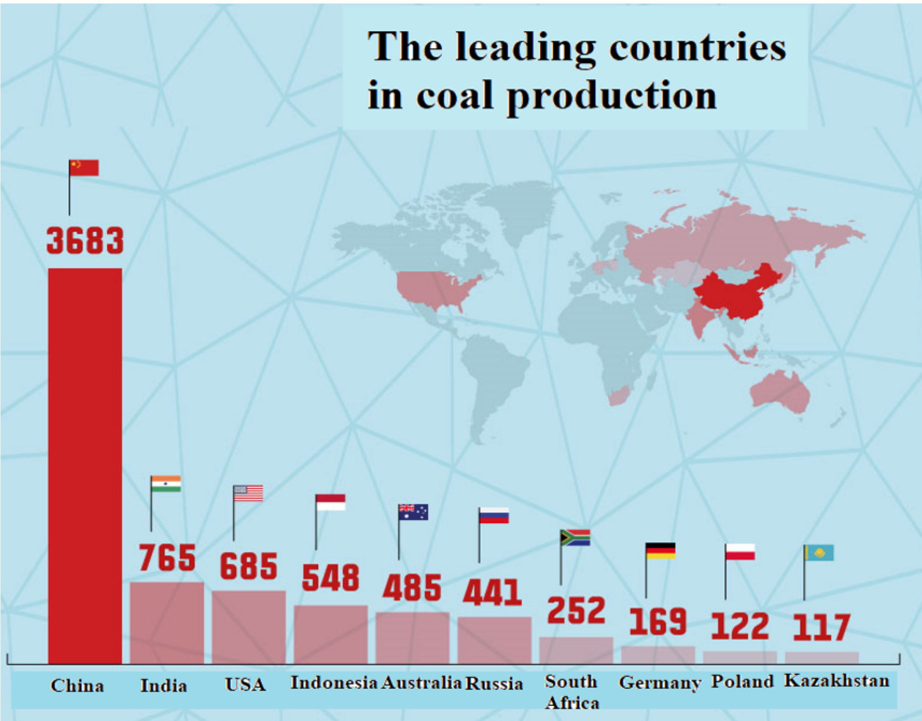

Fig. 1. The leading countries in coal production

There are various methods for reducing nitrogen oxide emissions, the most appropriate of which is the introduction of nitrogen oxide suppression technology at the stage of fuel combustion in the combustion chamber. Staged fuel combustion – Overfire Air (OFA) technology is one of the effective methods for reducing the concentration of nitrogen oxides NOx. Stepped air supply into the combustion space with OFA technology consists of supplying the required volume of air for coal combustion as follows: 70-90% of the air is supplied to the burners and 10-30% through OFA injectors, which are located above the burner devices. In this case, a low-temperature combustion zone depleted in oxygen and enriched in fuel is created in the lower part of the combustion device, which makes it possible to reduce the formation of NOx from fuel nitrogen (fuel NOx). At the same time, the low temperature in the oxygen-enriched zone of OFA injectors leads to minimization of the formation of NOx from the air (thermal NOx) (Bartlomiej, 2019; Messerle, 2004; Muller, 1994).

This article suggests the introduction of modern technology of OFA ignition and stabilization of pulverized coal fuel at Kazakhstan thermal power plants, using the latest information technologies and methods of 3D computer modeling methods. This will allow to optimize the processes occurring when burning high-ash energy fuel, to reduce harmful dust and gas emissions into the atmosphere (carbon oxides, nitrogen oxides, ash, etc.), to create and introduce in the future a method of obtaining "clean" energy.

All of the above stated the main goal of the work – the study of heat and mass transfer processes in high-temperature and two staged fuel combustion of pulverized coal fuel in a real physical and chemical system (combustion chambers of TPPs) in order to introduce the newest technologies of "clean energy" production in Kazakhstan.

Materials and Methods

In this paper, we study the heat and mass transfer in a high-temperature media through using a physical-mathematical model and a chemical model. These models include the following: 3D Navier-Stokes equations, heat and mass transfer equations with the source terms – they related to the chemical kinetics, nonlinear effects of thermal emission, interphase interaction, and multistage chemical reactions (Baizhuma, 2018).

The general view for heat and mass transfer equations in the boiler furnace is the following:

$$\frac{\partial \rho \varphi}{\partial t} = -\frac{\partial \rho u_i \varphi}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\Gamma_\varphi \frac{\partial \varphi}{\partial x_i}\right) + S_\varphi \quad (1)$$

where φ is a generalized transport variable, Γ_φ is a generalized coefficient of transfer, S_φ is the source of term (defined by the chemical kinetics of the process), nonlinear effects of thermal radiation and interphase interaction, and the multistage nature of chemical reactions. The system of equations (1) is solved numerically using the control volume method.

Modelling of heat and mass transfer processes in combustion chambers of operating power boilers allows solving complex problems of heat and power engineering and ecology related to reduction of emission of pollutants such as hydrocarbons CnHm, soot, CO, CO2 and NOx carbon oxides by controlling the regularities of temperature and fuel concentrations and oxidizer, which are fed in the area of their combustion.

In this paper, a computer software package FLOREAN was used as the basis for computational experiments to study heat and mass transfer processes using 3D modeling in the combustion chamber of a TPP boiler. This software package is widely used for calculations and research in the field of processes of highly reactive streams in the combustion chambers of many heat power plants. The FLOREAN application software package has been developed and developed for more than a decade due to the painstaking work of the team of German scientists, such as Von Muller (1992), Vockrodt (1995), Schiller (1999), Pauker (2001), Hoppe (2005) and Noack (2010) at the University of IWBT Germany.

This software package was adapted by us for carrying out computational experiments on numerical modelling of the combustion of high-ash solid fuel, which was plasma-trained, at Kazakhstan thermal power plants.

Computational experiments on the implementation of two-stage fuel combustion technology using the example of the combustion chamber of the BKZ-75 boiler at the Shakhtinskaya TPP. The BKZ-75 boiler is equipped with four pulverized coal burners, two burners installed at the front and at the rear in one tier. The boiler burns dust from Karaganda ordinary (KR-200) coal with an ash content of 35.1%, a volatile yield of 22%, a humidity of 10.6% and a calorific value of 18.55 MJ/kg. The general view of the combustion chamber of the BKZ-75 boiler (Figure 2a) and the arrangement of burners and injectors for the implementation of the technology of two-stage fuel combustion (Figure 2b) is shown (Messerle, 2019; Aliyarov, 2012; Ustimenko, 1982; Chibyshev, 2018).

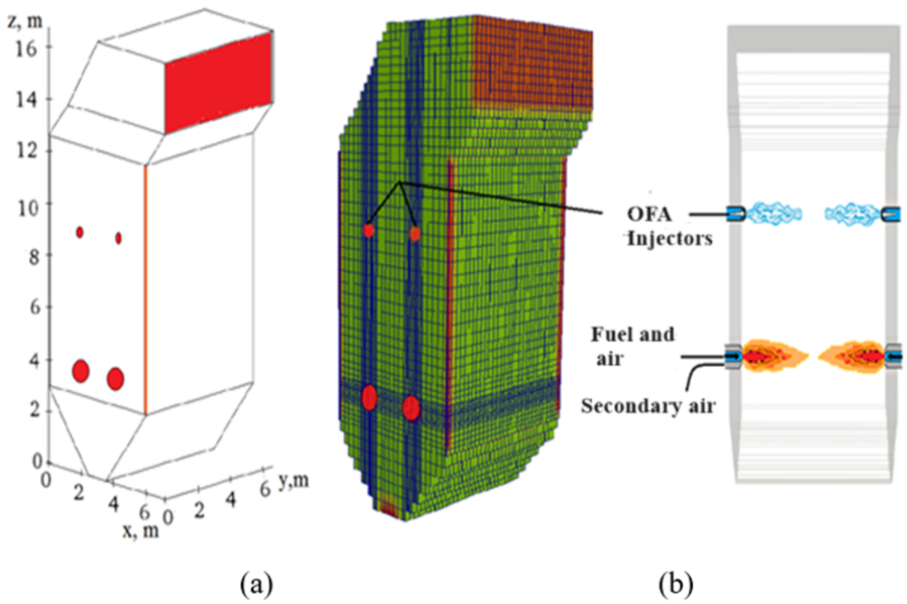

Fig. 2. General view of the combustion chamber of the BKZ-75 boiler at the Shakhtinskaya TPP (a), its breakdown into control volumes (b), the layout of burner devices and OFA injectors, and the three-dimensional distribution of the concentration of nitrogen dioxide NO2 along the height h of the combustion chamber of the BKZ-75 boiler at different volumes of air supplied through the injectors

Results and Discussion

Using computer modeling methods, various modes of supplying additional air to the combustion chamber of the BKZ-75 boiler through OFA injectors were studied: OFA=0% (basic version), OFA=10%, OFA=18%. As a result of the computational experiments, the distributions of concentrations of carbon oxides CO and nitrogen dioxide NO2 throughout the entire volume of the combustion chamber were obtained.

Figure 3 shows two-dimensional graphs of the distribution of the cross-section average temperature T along the height h of the furnace for the studied regimes of additional air supply. Its distribution over the height of the combustion chamber of the BKZ-75 boiler at different volumes of air supplied through OFA-injectors. At the outlet from the combustion chamber, we have a further decrease in temperature. Therefore, the average value of the temperature at the outlet from the combustion chamber is for OFA=0%, T=885.790C; OFA=10%, T=865.900C and OFA=18% T= 856.270C. The temperature distribution over the height of the combustion chamber is confirmed by experimental data (Figure 3) obtained directly at the operating Shakhtinskaya TPP (Zenkov, 2021; Korovyakovskiy, 2023; Ermolin, 2017, and at the outlet from the furnace space, its theoretical value, calculated by the CBTI method (Sheverdyaev, 2014; 2017) for the basic version (OFA=0%). Comparing the results obtained, it can be noted that with an increase in the volume of air supplied through the OFA injectors, a shift in the location of the flame core and an increase in the length of the zone of maximum temperatures are observed (Figure 3, curves 2, 3).

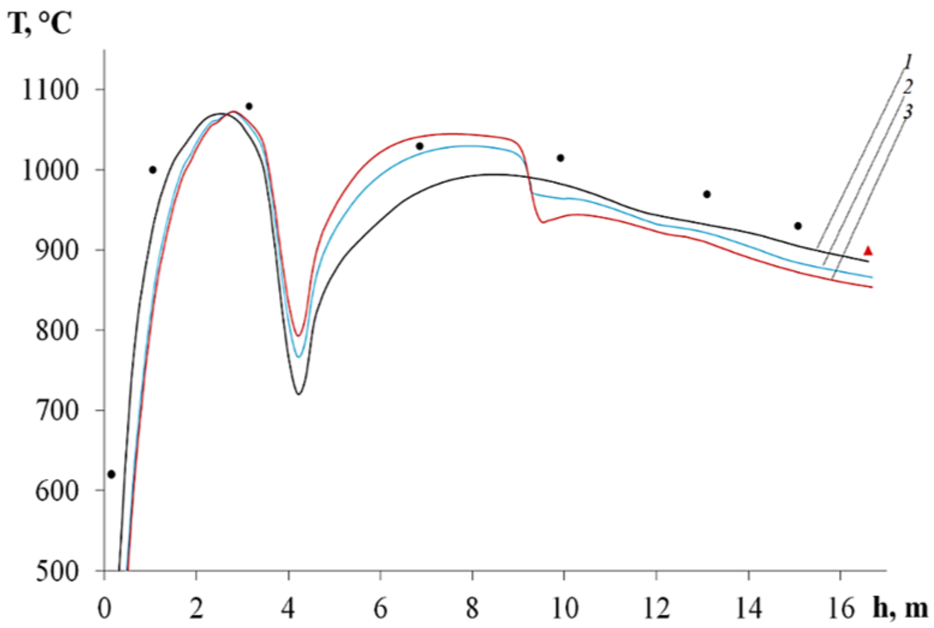

Fig. 3. Two-dimensional temperature distribution T along the height h of the furnace of the BKZ-75 boiler at various volumes of air supplied through the injectors:
1 – OFA=0%, 2 – OFA=10%, 3 – OFA=18%, – thermal power experiment (Zenkov, 2017; Globina 2021), red triangle – theoretical value obtained by the CBTI method (Sheverdyaev, 2014; 2017)

Figure 4 shows a graphical interpretation of the distribution of the concentration of nitrogen dioxide NO2 in the central (y = 3.3 m) section of the furnace of the BKZ-75 boiler for three options for supplying additional air through the injectors: a) OFA=0% (basic version), b) OFA=10%, c) OFA=18%. Analysis of Figures 4a, 4b and 4c shows that most of the nitrogen dioxide NO2 is formed in the active combustion zone located in the zone of the burners. It is this region that is characterized by high values of the temperature of the two-phase flow and the concentration of nitrogen dioxide NO2, which decreases along the height of the furnace.

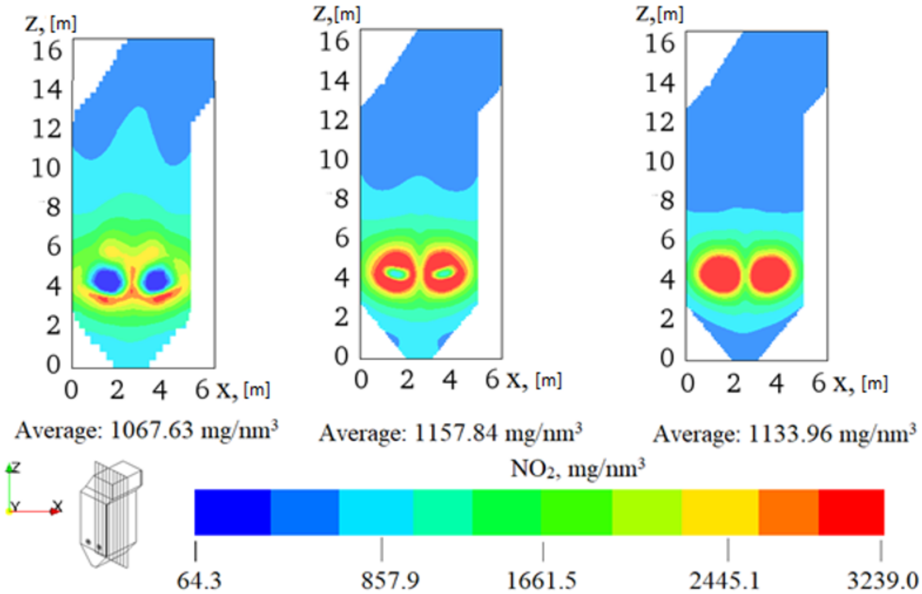

Fig. 4. Distribution of nitrogen dioxide NO2 concentration in the central section (y = 3.3 m) of the furnace of the BKZ-75 boiler with different volumes of air supplied through the injectors: (a) OFA = 0%, (b) OFA = 10%, (c) OFA = 18%

Conclusion

Based on the results of studies of the effect of introducing a two-stage combustion technology in the furnace of the BKZ-75 boiler, the following conclusions can be drawn:

1. As the volume of air supplied through the OFA injectors increases, the temperature in the zone where the burners are located increases. The use of two-stage combustion technology causes a decrease in the oxygen concentration in the zone of the most intense combustion (in the zone burner), which leads to a decrease in the total excess air ratio in this zone and to an increase in the flame temperature in this zone.

2. The temperature distribution over the height of the furnace is confirmed by experimental data obtained directly at the operating Shakhtinskaya TPP, and at the outlet from the combustion space with its theoretical value calculated using the CBTI method for the basic (OFA=0%). This confirms the adequacy of the models used in the numerical formulation of the problem.

3. The use of the technology of two-stage combustion in the furnace of the BKZ-75 boiler at Shakhtinskaya TPP leads to a significant decrease in the concentration of carbon monoxide CO and nitrogen dioxide NO2. One of the optimal options for reducing them at the outlet from the furnace is the use of injectors at OFA=18%.

The modern methods of physical, mathematical and 3D computer modeling presented in the work make it possible to study the processes of turbulent heat and mass transfer and the formation of harmful substances during the combustion of solid fuel in the combustion chambers of real energy facilities. The obtained results of the influence of the design parameters of the combustion chamber, various layouts of burner devices and the method of supplying the fuel air mixture on the main characteristics of the heat and mass transfer process (flow aerodynamics, temperature distribution and concentration of combustion products) will allow optimizing the process of burning low-grade fuel not only in the combustion chamber of the BKZ-75 boiler at the Shakhtinskaya TPP , but at other coal-burning thermal power plants of the Republic of Kazakhstan.

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