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ANALYSIS OF METHODS FOR REDUCING HARMFUL EMISSIONS FROM COAL-FIRED POWER STATIONS USING COMPUTATIONAL MODELING TECHNIQUES

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Abstract. The coal-fired power industry is a significant source of environmental pollution. Nowadays, thermal power plants mostly use coal as fuel. As a result, combustion produces nitrogen oxides, leading to stricter requirements for the energy industry. This research is devoted to heat and mass transfer processes during pulverized coal combustion with the use of OFA technology to reduce harmful emissions. The authors developed the geometry and partitioning of the computational domain into control volumes and generated a mathematical model of pulverized coal flame. Based on the results of computational experiments, a graphical interpretation of the obtained results and their verification was carried out, allowing the authors to confirm that the introduction of OFA technology can significantly reduce the amount of nitrogen oxides.

Keywords: coal-fired power station, coal combustion, OFA-technology, energy industry, computational modeling

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АНАЛИЗ СПОСОБОВ СНИЖЕНИЯ ВРЕДНЫХ ВЫБРОСОВ УГОЛЬНЫХ ТЭС С ПРИМЕНЕНИЕМ МЕТОДОВ КОМПЬЮТЕРНОГО МОДЕЛИРОВАНИЯ

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Аннотация. Угольная энергетика представляет собой значительный источник загрязнения окружающей среды. На сегодняшний день, тепловые электростанции по большей части используют в качестве топлива уголь, в результате сжигания которого образуются оксиды азота, что приводит к ужесточению требований к предприятиям энергетической отрасли. Данное исследование посвящено процессам тепломассопереноса при сжигании пылеугольного топлива при использовании OFA-технологии для снижения вредных выбросов. В ходе исследования была разработана геометрия и разбивка на контрольные объемы расчетной области, сформулирована математическая модель горения пылеугольного факела. По результатам вычислительных экспериментов на основе полученных данных была проведена графическая интерпретация полученных результатов и их верификация, подтверждающая, что внедрение технологии OFA позволяет существенно снизить количество образуемых оксидов азота.

Ключевые слова: угольная ТЭС, сжигание угля, OFA-технология, угольная энергетика, компьютерное моделирование

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Introduction

Nitrogen oxides, predominantly NO and NO2, and partly N2O, produce the maximum photochemical smog. For instance, when oxidized to higher oxides, they can provoke acid rain, which is extremely harmful to plants and animals, buildings, and cultural and architectural monuments. Formation of nitrogen oxides occurs during combustion due to oxidation of air nitrogen at high temperatures and nitrogen in the fuel, which is present in complex organic coal compounds. 10–30% of fuel nitrogen is converted into nitrogen oxide (II) NO. Leaving the chimney stack, nitrogen dioxide (NO2) makes 10-15%, while the remaining 85-90% is mainly NO. What is more, the amount of nitrogen dioxide increases to 60–70% as the flue stream moves through the atmosphere (Ol'khovskii, 1996; Mcmullan, 2001; Kulikov, 2009; Messerle, 2021; Askarova et al., 2024).

A two-stage combustion method is considered most efficient in reducing the amount of nitrogen oxides formed directly in the combustion chamber. This method relies on dividing the combustion chamber volume into oxidizing and reducing zones. hereby, part of the air required for complete combustion of the fuel is supplied above the combustion zone. As a result, air depletion results in a temperature reduction in the combustion chamber, ultimately decreasing the thermal oxides (Wilde, 2008). Above the flame area, lower temperatures contribute to reduction of afterburning products of incomplete combustion (CO to CO2) and reconstruction of nitrogen oxide to molecular nitrogen (Askarova, 2021).

It is also important to note that the intensity of the combustion process of a coal particle is largely determined by the rate of oxidizer supply to its surface. The air supply above the combustion area can occur at high speed (depending on the number, size, and arrangement of diluent air nozzles). Thus, the vortex in the combustion chamber makes it possible to intensify the combustion process. The research by (Dyusenova, 2005; Kuang, 2012; Huang, 2006; Liu, 2005; Le Bris, 2007; Cremer, 2002, 2003; Valentine, 2003; Wang, 2015; Askarova, 2012) is focused on specific features of different OFA nozzle layouts and combustion chamber designs. In order to optimize the combustion of energy fuel and minimize harmful emissions, there is a strong need to conduct studies of heat and mass transfer processes. Computational modelling proves to be the most relevant and efficient method of all. Despite the entire variety of challenges associated with computational experiments, it is possible to achieve high accuracy if an adequate physical and mathematical model is designed.

Materials and Methods

This research employed the FLOREAN software package in association with the control volume approach. This strategy implies that the computational domain is divided into a grid, forming a set of finite volumes. The solutions of the basic equations (continuity, motion, energy, and components) are calculated in the centers of these volumes.

The case study is carried out on the basis of the combustion chamber of a PK-39 steam boiler installed at Aksu power plant, operating on Ekibastuz coal. Figure 1 shows the layout of the boiler: a) for traditional pulverized coal combustion, b) with OFA supplementary air nozzles. The main design features are presented in Table 1.

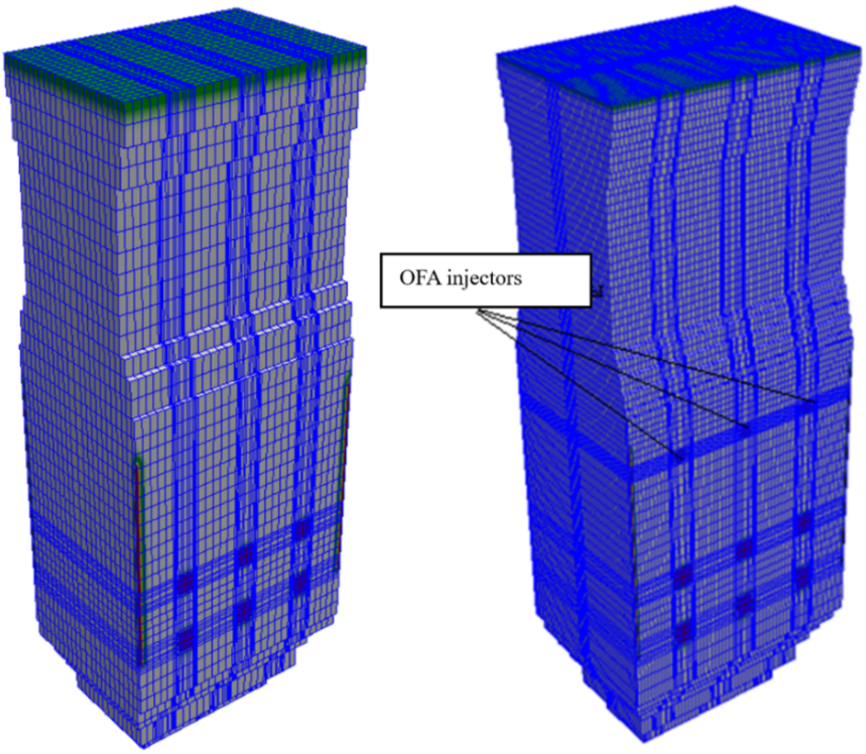

Fig. 1. PK-39 boiler and its layout with control volumes: a) base case, b) with OFA nozzles implemented.

Table 1. Design characteristics of PK-39 boiler with air staging (Aksu TPP)

Design characteristics	Size/number
Elevation of combustor, meters	29.985
Width of combustor, meters	10.76
Depth of combustor, meters	7.762
Number of burners	12
Number of OFA noozles	6
Elevation of the of the lower burner tier, meters	7.315
Elevation of the of the higher burner tier, meters	10.115
Elevation of OFA nozzles tier, meters	15.735
Size of lower burners, meters	1.2
Size of higher burners, meters	1.05
Size of OFA noozles, meters	0.7

A system of differential equations (1-4) is employed for the description of three-dimensional motion of a medium with variable physical properties, velocity, temperature, and concentration. The control volume method is used to derive data on balance correlation.

$$\frac{\partial \rho}{\partial t} = -\frac{\partial}{\partial x_i}(\rho u_i) \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) = -\frac{\partial}{\partial x_j}(\rho u_i u_j) + \frac{\partial}{\partial x_j}(\tau_{i,j}) - \frac{\partial \rho}{\partial x_j} + \rho f_i \tag{2}$$

$$\frac{\partial}{\partial t}(\rho h_i) = -\frac{\partial}{\partial x_i}(\rho u_i h) - \frac{\partial q_i}{\partial x_i} + u_i \frac{\partial \rho}{\partial x_i} + \tau_{ij} \frac{\partial u_j}{\partial x_i} + S_q \tag{3}$$

$$\frac{\partial}{\partial t}(\rho c_\beta) = -\frac{\partial}{\partial x_i}(\rho c_\beta u_j) + \frac{\partial}{\partial x_i} + R_\beta \tag{4}$$

where i = 1,2,3; j = 1,2,3; β = 1,2,3,...,N.

The well-known K-ε turbulence model is used to model turbulent viscosity. The given model involves the equation of conservation of turbulence kinetic energy (K), its dissipation rate (ε), and a model relation for turbulent viscosity. It is a standard flow model with forced and natural convection.

A system of differential equations (1-4) is used for three-dimensional motion of a medium with variable physical properties, velocity, temperature, and concentration. The control volume method is used to derive data on balance correlation. (Chikobvu, 2023).

$$\frac{\partial \rho}{\partial t} = -\frac{\partial}{\partial x_i}(\rho u_i) \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) = -\frac{\partial}{\partial x_j}(\rho u_i u_j) + \frac{\partial}{\partial x_j}(\tau_{i,j}) - \frac{\partial \rho}{\partial x_j} + \rho f_i \tag{2}$$

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$$\frac{\partial}{\partial t}(\rho c_\beta) = -\frac{\partial}{\partial x_i}(\rho c_\beta u_j) + \frac{\partial}{\partial x_i} + R_\beta \qquad (4)$$

where i = 1,2,3; j = 1,2,3; β = 1,2,3,...,N.

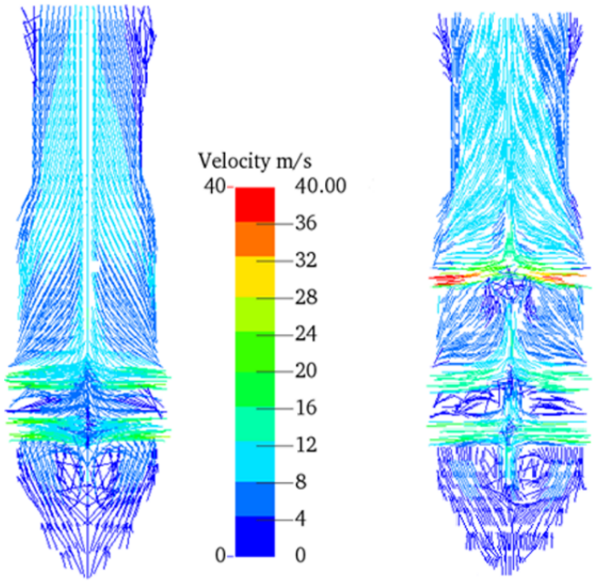
When considering heat transfer processes in technical reacting flows in combustion chambers, heat via radiation makes the largest contribution to the total heat transfer. In the flame zone, the contribution of radiant heat transfer makes up to 90% or more (Saparov, 1990). Consequently, modelling heat transfer by radiation in reacting flows is one of the most important stages in calculations of heat and mass transfer processes in real combustion chambers. The six-flow model in Cartesian coordinates proposed by De Marco and Lockwood is used to describe radiative heat transfer. In this model, the distribution of the radiant energy flux at the corresponding sections is approximated via series and spherical functions.

Results and Discussion

This research considers the cases with the percentage of air supplied through the OFA nozzles equal to 0 (base case), 10 and 20% of the total amount of secondary and tertiary air supplied to the furnace chamber. Aerodynamic, thermal, and concentration features of staged combustion of pulverized coal fuel were investigated on the example of the PK-39 boiler, Aksu TPP.

Comparative analysis on Figures 2-4 shows that the aerodynamic properties of pulverized coal flame combustion differ from the base case when additional OFA nozzles are introduced. Specifically, flame shape and velocity distribution have changed, and turbulization of flows starts to be observed in the area of OFA nozzles.

At the furnace exit (Fig. 4), the vortex flow does not weaken significantly compared to the base case of pulverized coal combustion. Subsequently, combustion products stay in the furnace chamber longer, which results in a greater reduction of nitrogen oxide NO to molecular nitrogen N2.



a)

b)

Fig. 2. Distribution of velocity vector in the central section of the furnace chamber, PK-39 boiler:
a) OFA=0%, b) OFA=20%

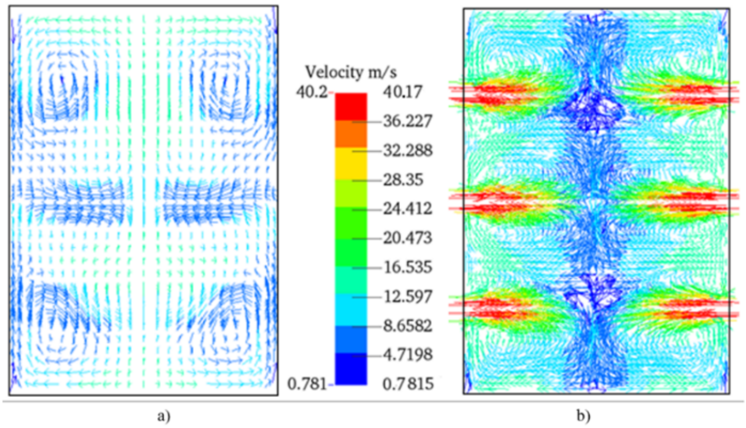


Fig. 3. Distribution of the velocity vector in cross-section of the furnace chamber PK-39 boiler in the area of OFA nozzles: a) OFA=0%, b) OFA=20%

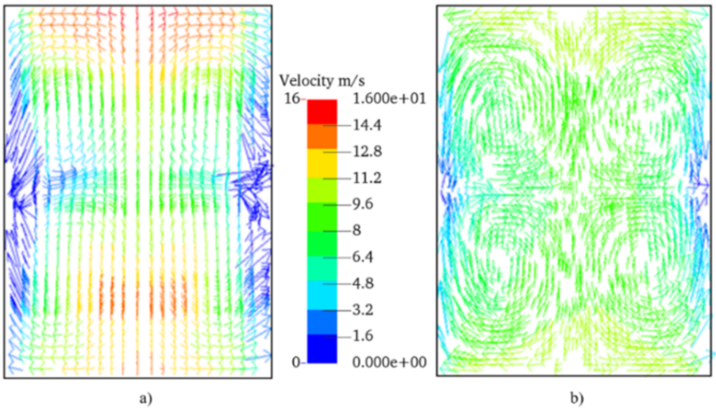


Fig. 4. Distribution of velocity vector at the furnace exit, PK-39 boiler:
a) OFA=0%, b) OFA=20%

A number of tendencies are evident from the analysis of temperature distribution in the furnace chamber. According to Figures 5-6, we can see that the excess air ratio around burners reduces when a part of air is supplied from above the zone of active combustion. At the same time, the temperature increases following the growing percentage of tertiary air and, in turn, desrease in the area of OFA nozzles (Fig. 5). Moving towards the furnace exit, the temperature field equalizes and the differences in the values of the average temperature for different cases decrease. At the exit, the difference in the average values amounts to 13.6 °C (Fig. 6).

Verification of the results shows good correspondence between the obtained and experimental data. First of all, the greatest differences are observed in the area of ignition of the pulverized coal mixture. What is more, on the way to the furnace exit, these differences become almost insignificant. Thus, the implemented models prove to be efficient and adequate for the research.

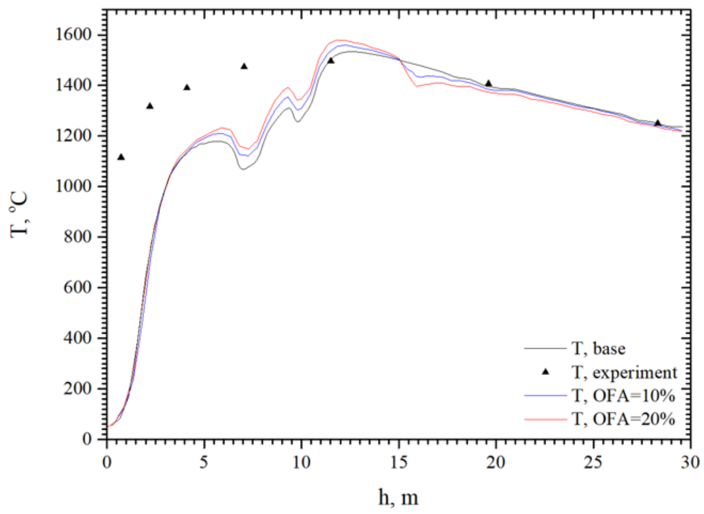


Fig. 5. Temperature distribution along the height of the furnace chamber, PK-39 boiler

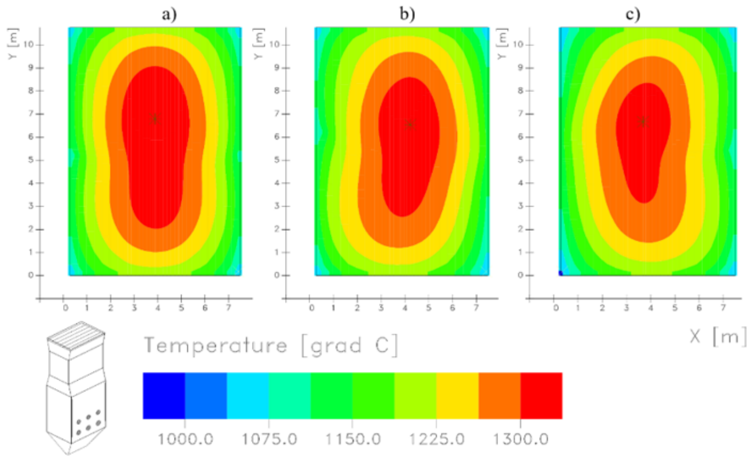


Fig. 6. Temperature distribution at the furnace exit (Z=29,60 m), PK-39 boiler:
a) OFA=0%; b) OFA=10%; c) OFA=20%

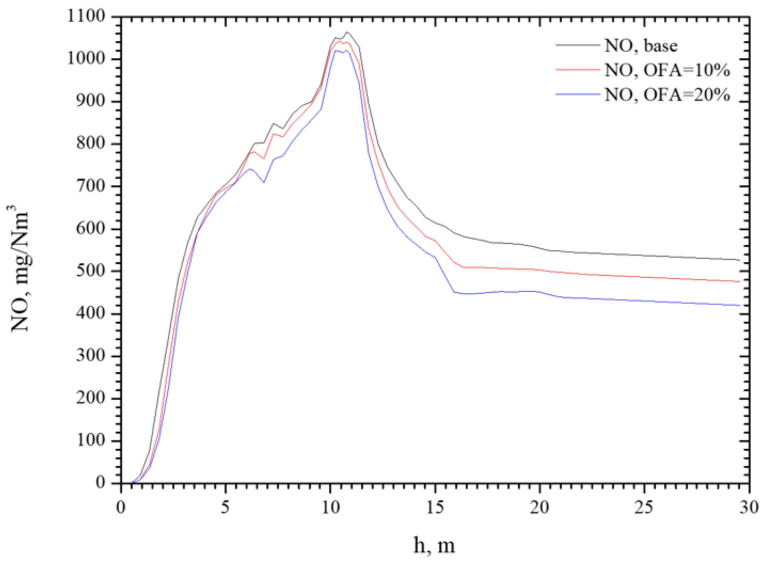


Fig. 7. Distribution of NO concentration over the height of the furnace chamber

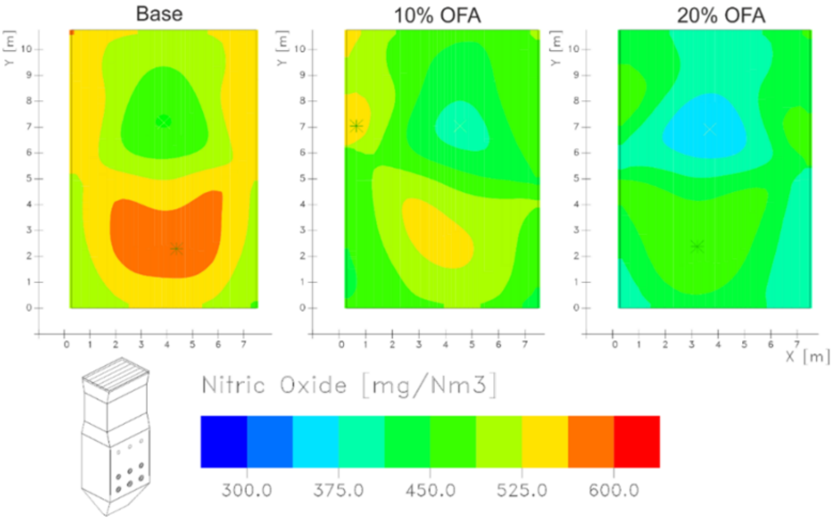


Fig. 8. Distribution of NO concentration at the furnace exit, PK-39 boiler

Analysis of NO concentration and distribution (Fig. 7-8) proves that increasing the air supply via the OFA nozzles allows to significantly reduce the concentration of nitrogen oxide at the furnace exit. It results from the fact that a bigger mass flow rate of air supplied through the OFA nozzles leads to a decrease in NO concentration in the entire volume of the furnace chamber (Fig. 7) and its exit (Fig. 8). This observation is confirmed by the well-known dependence of temperature-produced NO and temperature distribution (Fig. 5-6) in the furnace chamber.

Conclusion

Computational experiments on the OFA technology show that its introduction will lead to changes in the distribution of temperature and concentrations of carbon oxides (CO) and (CO2), as well as nitrogen oxide (NO) in the furnace space (case-based: PK-39 boiler, Aksu TPP). The most important outcome is the reduction of NO concentration at the furnace exit with the OFA amounting to 20%. Overall, OFA technology is one of the most promising ways to reduce harmful emissions (nitrogen oxide and carbon dioxide) into the atmosphere when implemented in the combustion of high-ash fuels in the furnace chambers of coal-burning TPPs.

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