Digital Tools for Combustion Management in the Tasks of Environmental Modernization of Energy Facilities

S. Bolegenova, A. Askarova, S. Bolegenova, A. Nugymanova, V. Maximov, Sh. Ospanova, S. Umarov
Department of Physics and Technology, Al-Farabi Kazakh National University, Almaty, Kazakhstan

A. Georgiev
Department of General Engineering, University of Telecommunications and Posts, Sofia, Bulgaria

INTRODUCTION

Modern energy systems must ensure reliable power supply while minimizing environmental impact. Coal-fired power plants remain important in many countries, including Kazakhstan, but they produce significant nitrogen oxide (NOx) emissions that degrade air quality and contribute to smog. Stricter environmental regulations increase the need for technologies that improve combustion efficiency and reduce emissions.

One effective solution is Overfire Air (OFA) technology, based on staged combustion: primary air is supplied to the lower furnace, while additional air is injected at higher levels. This improves fuel burnout, lowers peak temperatures, and reduces NOx formation. Its performance depends on air distribution and injector placement.

The challenge is greater when burning high-ash fuels such as Karaganda coal, which can lead to unstable combustion, higher emissions, and lower efficiency. In this case, numerical modeling is an effective tool for analyzing and optimizing combustion processes without costly experiments.

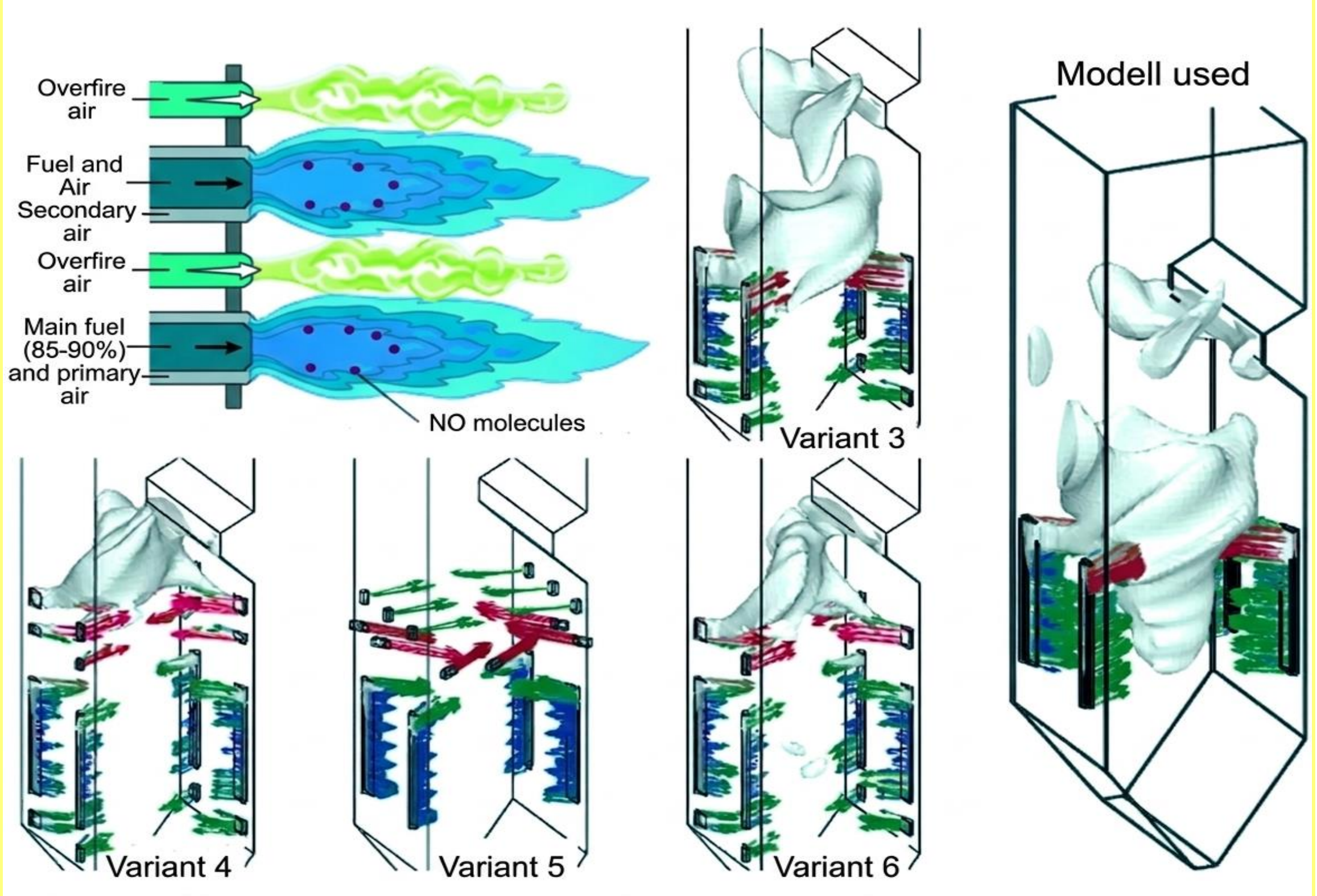


Fig. 1. Layout schemes of Overfire Air injectors and visualization of secondary air flow aerodynamics in the furnace space

This study focuses on a numerical investigation of OFA technology applied to a BKZ-75 boiler at the Shakhtinsk thermal power plant. Different injector configurations and air supply rates are analyzed to assess their effects on temperature fields and NOx emissions. The results help determine optimal operating conditions for cleaner and more efficient combustion.

SIMULATION OF COAL COMBUSTION PROCESSES

The heat and mass transfer in high-temperature reactive media are analyzed using integrated physical, mathematical, and chemical models. These models are based on conservation equations for mass, momentum, species concentration, and energy. They account for non-isothermal and turbulent flow conditions, the multiphase nature of the medium, ongoing chemical reactions, and radiative heat transfer. In a generalized form, the governing equations can be expressed as [19–27]:

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

where ϕ-transport variable (mass, momentum, energy, concentration of components, kinetic energy of turbulence and its dissipation), Γϕ – 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 COMPUTATIONAL DOMAIN

For numerical experiments on NOx reduction using Overfire Air (OFA), the furnace chambers of the BKZ-75 (Kazakhstan) boilers were selected. This work focuses on the BKZ-75 furnace, a vertical water-tube boiler with a steam capacity of 75 t/h (51.45 Gcal/h).

It is equipped with four pulverized-coal burners arranged in a single level (two front, two rear). Karaganda coal dust is used as fuel (ash – 35.1%, volatiles – 22%, moisture – 10.6%, LHV – 18.55 MJ/kg).

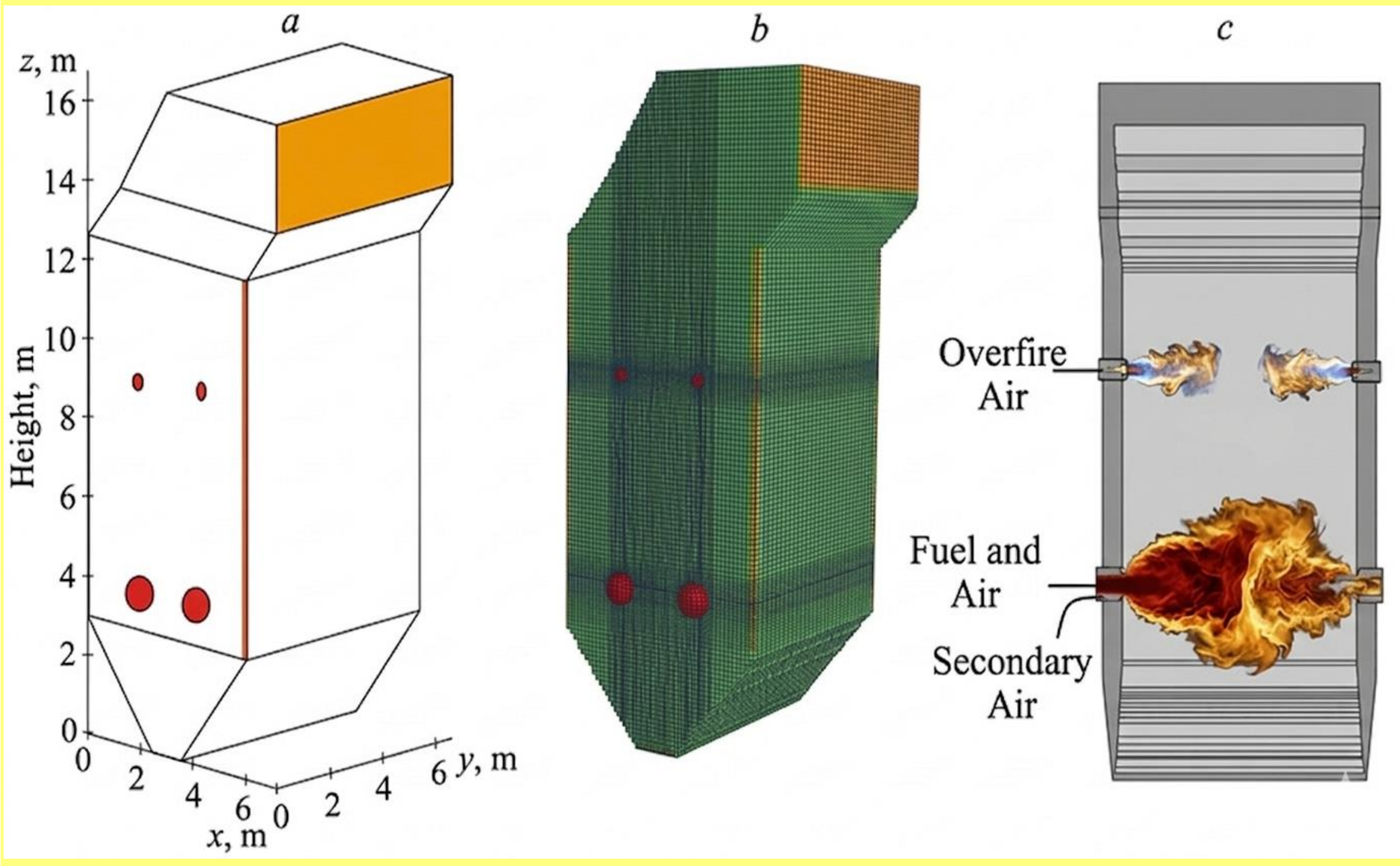
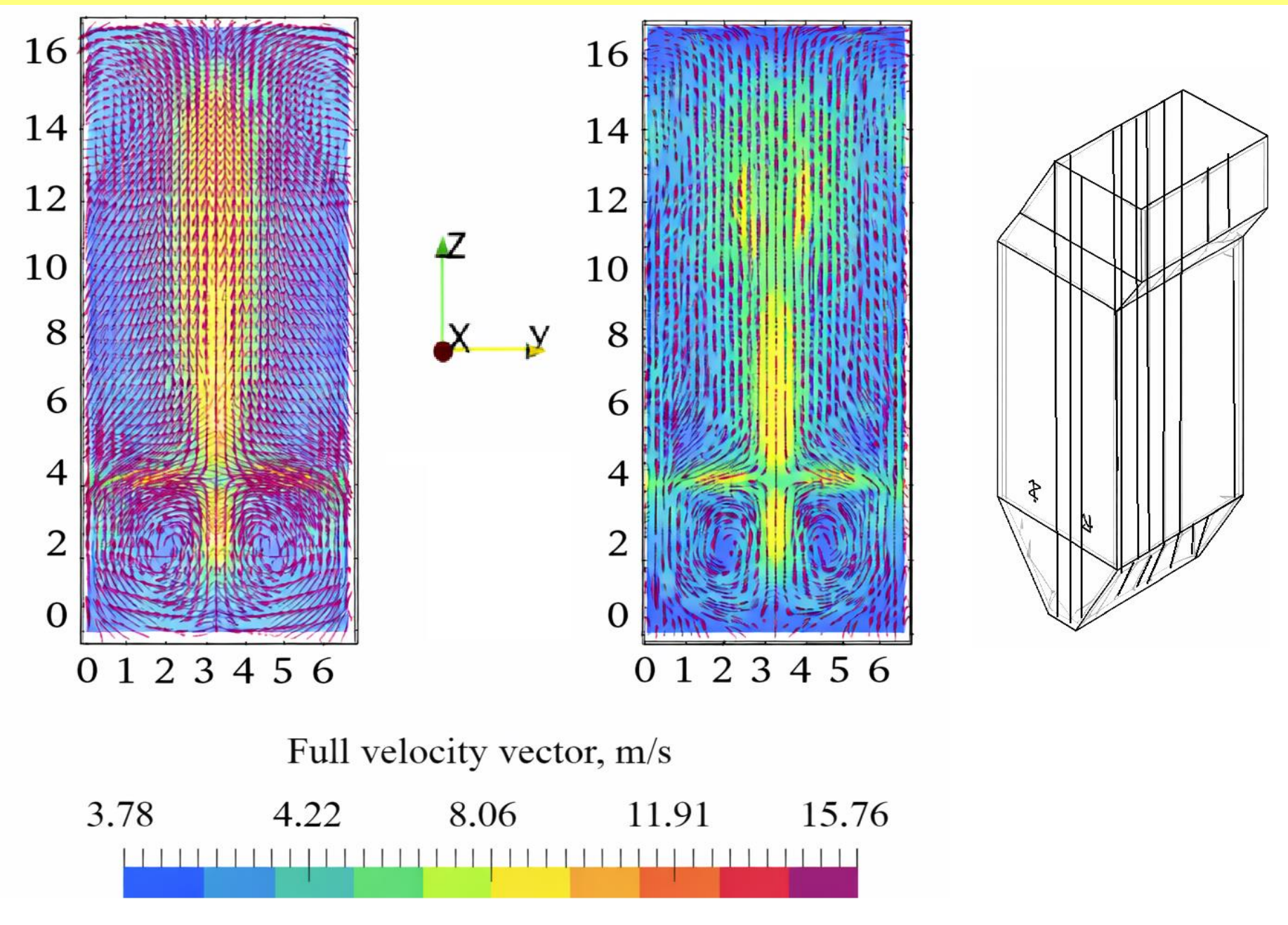


Fig. 2. BKZ-75 boiler furnace: general view (a), discretization of the computational domain into control volumes (b), layout of burners and OFA injectors (c).

The furnace geometry, burner configuration, and OFA injector layout were taken into account in the computational model. A finite-difference mesh of 90 × 32 × 158 cells along the X, Y, and Z axes was generated, resulting in 455,040 control volumes. This discretization provides sufficient accuracy for simulating aerodynamic, heat, and mass transfer processes within the furnace.

Using computational modeling methods, different air supply regimes were analyzed for the BKZ-160 and BKZ-75 boilers. For the BKZ-75 boiler, cases with OFA shares of 0% (baseline), 5%, 10%, 15%, 18%, and 20% were investigated. The simulations produced distributions of velocity vectors, temperature fields, and NO concentrations throughout the furnace volume. Based on these results, a comparative analysis of the operating regimes was performed.

Results



(a) (b)

Fig 3. Three-dimensional distribution of total velocity vectors in the longitudinal section of the furnace chamber for different air supply rates through OFA injectors: OFA = 0% (a) and OFA = 18% (b)

Analysis of the total velocity vector field in a longitudinal section (x = 3 m) of the BKZ-75 furnace for OFA = 0% and OFA = 18%. In both cases, the flame core is located in the center of the furnace and is formed by the interaction of opposing burner jets. Downstream, the velocity field becomes more uniform, and gas velocities decrease toward the furnace outlet.

Figure 4 presents the NO concentration distributions along the furnace height for the baseline case (0%) and for OFA operation (18%) in the BKZ-75 boiler. The analysis shows that the highest NO concentrations are formed in the lower furnace region, in the burner zone (flame core), where high temperatures, intensive fuel-air mixing, and strong chemical activity occur simultaneously.

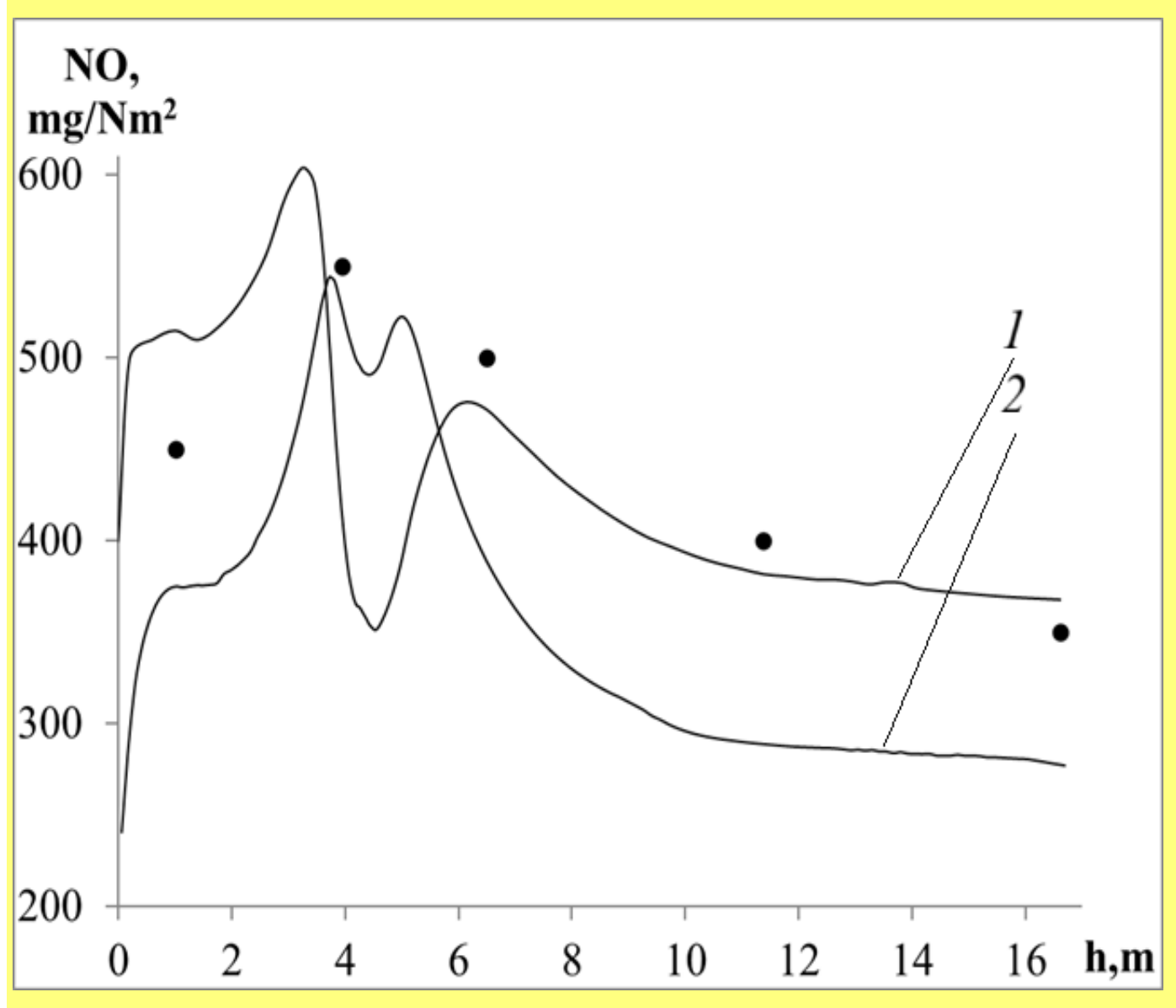


Fig 5. Two-dimensional NO concentration distribution along furnace height in the boiler BKZ-75: curve 1 – OFA=0%; curve 2 – OFA=18%; experimental data from TPP [5].

In the baseline regime, NO levels remain relatively high throughout the furnace up to the outlet. With staged combustion using OFA, a noticeable reduction in NO is observed in the upper furnace and at the outlet. Local variations near the OFA injection level are caused by dilution of combustion products with secondary air. In the lower furnace, a temporary increase in NO may occur due to intensified oxidation of fuel-bound nitrogen.

OFA application leads to flame elongation, more uniform heat release distribution, and lower exit gas temperatures. A fuel-rich zone is formed in the lower furnace, suppressing fuel-NO formation, while an oxygen-rich, lower-temperature zone at the OFA level limits thermal NO formation. As a result, NO concentrations decrease significantly along the furnace height, demonstrating the strong impact of OFA on emission reduction and flame structure.

Conclusions

Comparative analysis of the numerical simulation results shows that the application of OFA technology significantly affects the aerodynamic and thermal characteristics of the combustion process in the furnace volume. In the baseline case (without additional air), elevated NO concentrations persist along the entire furnace height up to the outlet section, which is typical for conventional single-stage combustion systems.

Acknowledgements

This work has been funded financially by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP26105185).

References

1. Askarova, A.S., et al. Modeling of heat and mass transfer in high-temperature reacting flows with combustion. High Temperature 56(5), 738–743 (2018). Messerle, V.E., et al. Optimization of the combustion of power station coals using plasma technologies. Thermal Engineering 51(6), 488–493 (2004).
2. Mazhrenova, N., et al. 3D modelling of heat and mass transfer processes during the combustion of liquid fuel. Bulgarian Chemical Communications 48(E2), 229–235 (2016).
3. Kang, W., et al. Numerical investigations on overfire air design for improved boiler operation and lower NOx emission in commercial wall-firing coal power plants. Applied Thermal Engineering 219(1), 119604 (2022).
4. Askarova, A., Georgiev, A., et al. Computational modeling of pollutants in furnaces of pulverized coal boilers of the Republic of Kazakhstan. Energy 258, 124826 (2022).
5. Aliyarov, B., et al. Combustion of Kazakhstan coals at TPPs and large boiler houses: experience and problems. Gylym Ordasy, Almaty, Kazakhstan (2012).