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MODELING COMBUSTION PROCESSES DURING FORCED SHUTDOWN OF BURNERS

This study numerically examines the aerodynamics, coupled heat and mass transfer, and pollutant formation in the BKZ-75 boiler furnace under an emergency scenario involving partial burner shutdown. The study is aimed at assessing the effect of two fuel–air mixture supply configurations, namely straight-flow and swirling injection, on the combustion behavior inside the furnace. The numerical calculations were used to examine the velocity field, temperature distribution, and NO_2 concentration both within the furnace chamber and at its outlet. In the straight-flow case, the gas motion remains more strongly stratified, with relatively weak turbulent mixing in the vertical direction and the formation of localized high-temperature regions. A noticeably different flow structure develops when swirl is introduced. Large-scale vortical structures promote a stable and efficient combustion process by providing more favorable velocity and temperature distributions, while the maximum NO_2 concentration is formed in the burner region. At the furnace exit, the calculated mean NO_2 concentration for the swirling configuration is about 8% lower than that obtained for the straight-flow case. Overall, the swirl method demonstrates higher environmental efficiency and operational stability. The identified flow and emission patterns can support further refinement of BKZ-75 burner geometry and fuel-air delivery schemes aimed at improving operating efficiency while limiting pollutant release.

Keywords: combustion, emergency operating conditions, harmful emissions, furnace chamber aerodynamics, temperature field, nitrogen oxides.

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Жанартықтардың мәжбүрлі өшірілуі кезіндегі жану процестерін модельдеу

Осы зерттеуде БКЗ-75 қазандығының оттық камерасында жанарғылардың бір бөлігі ажыратылған авариялық режим кезіндегі аэродинамика, жылу және масса алмасу, сондай-ақ ластаушы заттардың түзілуі сандық әдістермен зерттелді. Пештегі жану процестеріне екі отын-ауа қоспасын беру схемасының - тікелей және құйынды - әсері қарастырылады. Есептеулер жылдамдық пен температура өрістерін, сондай-ақ камера ішіндегі және оның шығысындағы NO_2 концентрациясының таралуын талдау үшін қолданылады. Тікелей беру әлсіз тік турбулентті араластырумен және жергілікті жоғары температуралы аймақтардың пайда болуымен қатар жүретін айқын ағын стратификациясына әкеледі. Үлкен құйындар жылдамдық пен температура сияқты параметрлер бойынша тиімді және тұрақты жануды қамтамасыз етеді, ал оттық аймағында азот диоксидінің максималды мөлшері түзіледі. Құйынды беру кезінде пештің шығысындағы NO_2 орташа концентрациясы тікелей берумен салыстырғанда шамамен 8%-ға төмен. Жалпы алғанда, құйынды дизайн қоршаған ортаның жақсырақ өнімділігін және қазандықтың тұрақты жұмысын қамтамасыз етеді. Анықталған үлгілерді тиімділікті арттыру және шығарындыларды азайту үшін БКЗ - 75оттық геометриясын және отын мен ауа беру жүйелерін одан әрі жетілдіру үшін пайдалануға болады.

Түйін сөздер: жану, авариялық жұмыс режимдері, зиянды шығарындылар, оттық камерасының аэродинамикасы, температура өрісі, азот оксидтері.

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Моделирование процессов горения при вынужденной остановке горелок

В работе численно исследованы аэродинамика, сопряженный тепло- и массообмен и образование загрязняющих веществ в топочной камере котла БКЗ-75 при аварийном режиме, связанном с частичным отключением горелок. Рассмотрено влияние двух схем подачи топливно-воздушной смеси — прямоточной и вихревой — на процессы горения в топке. На основе расчетов проанализированы поля скоростей и температуры, а также распределение концентрации NO_2 в объеме камеры и на ее выходе. При прямоточной подаче формируется более выраженная стратификация потока, сопровождаемая слабым вертикальным турбулентным перемешиванием и появлением локальных высокотемпературных зон. Крупные вихри обуславливают эффективно-стабильное протекание процесса горения по таким параметрам как скорость и температура, при этом максимальное количество диоксида азота образуется в области горелки. При вихревой подаче средняя концентрация NO_2 на выходе из топки примерно на 8 % ниже, чем при прямоточном режиме. В целом вихревая схема обеспечивает более благоприятные экологические характеристики и более устойчивую работу котла. Выявленные закономерности могут быть использованы при дальнейшем совершенствовании геометрии горелок БКЗ-75 и схем подачи топлива и воздуха с целью повышения эффективности работы и снижения выбросов.

Ключевые слова: сгорание, аварийные режимы работы, вредные выбросы, аэродинамика камеры сгорания, температурное поле, оксиды азота.

Introduction

Energy-related activities remain the dominant contributor to anthropogenic greenhouse-gas emissions and therefore continue to intensify the climatic warming trend [1]. International Energy Agency (IEA) statistics show that the global primary-energy balance is still governed mainly by fossil resources, namely oil, natural gas, and coal.. In 2024, global energy demand increased by 2.2%, with renewable energy sources accounting for 38% of the growth, followed by natural gas (28%), coal (15%), oil (11%), and nuclear energy (8%). Even with more than 750 GW of renewable capacity added in 2025, about four-fifths of it photovoltaic, fossil fuels still supplied roughly two-thirds of the increase in worldwide energy consumption.. Accordingly, energy-sector CO_2 emissions climbed to 38.0 Gt in 2025, establishing a new maximum and exceeding the 2024 level by 0.8%.

The global community is stepping up efforts to decarbonize the global economy by 2050, including carbon pricing mechanisms (carbon taxes and allowances) and climate adaptation. The Paris Agreement remains a catalyst for carbon neutrality: the European Union, the United Kingdom, Japan, the Republic of Korea, and over 110 other countries have reaffirmed their goals of achieving net-zero emissions by mid-century. Nevertheless, the 2025 indicators remained adverse: emissions reached record levels and atmospheric CO_2 rose to 423.5 ppm, approximately 1 ppm above 2024, against a background of extreme weather, growing cooling demand, and expanding electricity use by data centers.

Although renewable power generation continues to expand rapidly, coal-fired power plants still remain an important source of controllable electricity in many energy systems, particularly in regions where security of supply and grid stability are major operational concerns. IEA data indicate that global coal demand increased by about 1.2% in 2024, reaching approximately 8.79 billion tonnes, while only marginal growth, to nearly 8.8 billion tonnes, is expected in 2025 [2]. This relatively stable demand is largely associated with the power sector. Coal-based electricity generation was estimated at about 10,800 TWh in 2025 and continues to contribute to system balancing, especially during periods when output from variable renewable sources is constrained by weather conditions or insufficient storage capacity. Consequently, CO_2 emissions associated with coal use showed a slight increase in 2025, partly counteracting emission reductions achieved in several

other sectors. These developments illustrate the persistent tension between near-term requirements for reliable electricity supply and longer-term decarbonization targets. In this context, further progress depends not only on the deployment of low-carbon and energy-storage technologies, but also on improving the efficiency and flexibility of existing coal-fired generation in order to reduce its environmental impact during the transition period.

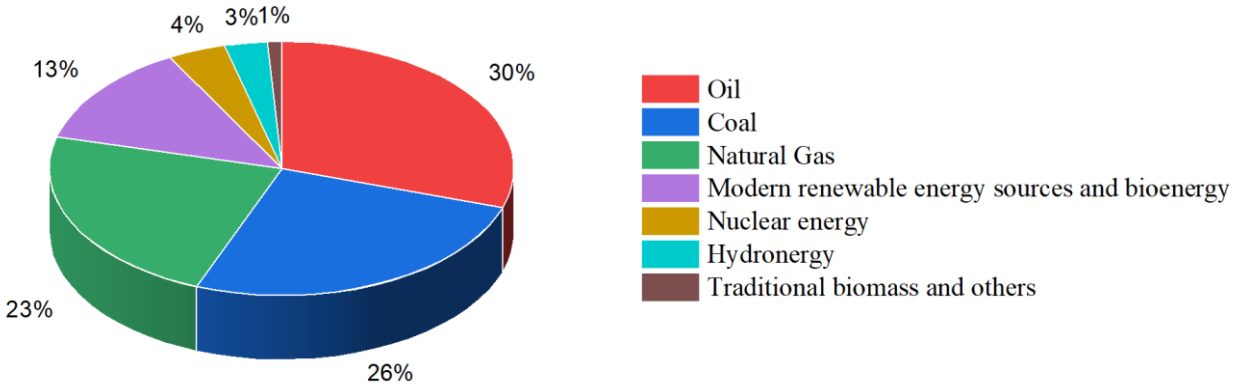


Figure 1 – Shares of fuel in global primary energy supply in 2025 [2]

The coal industry faces a fundamental paradox: positioned as the most polluting source in the context of the green transition, it remains an economically accessible and technologically reliable resource amid escalating global demand. In leading countries declaring carbon neutrality by 2050-2060, a radical reduction in coal-fired generation is unfeasible in the short term due to the risk of energy crises. Given the sustained high cost of natural gas, rapidly increasing electricity demand in Asia, and continuing industrial development in China, India, and Southeast Asian countries, a substantial decline in coal use appears unlikely in the near term. Coal is therefore expected to remain an important component of the energy mix for at least the next 5–10 years [3–6].

In response to environmental challenges, "clean coal" technologies are being actively implemented: super- and ultra-supercritical units (efficiencies up to 49%, CO_2 reduction by 20–30%), circulating fluidized bed boilers, and modern DeSOx/DeNOx/dust collection systems. These solutions allow for a radical reduction in SOx, NOx, particulate matter, and some CO_2 emissions without completely eliminating coal.

Coal-fired power generation continues to play a key role in ensuring economic stability and the well-being of the population in many countries [7–11]. Under these conditions, a more detailed analysis of furnace combustion becomes essential in order to identify operating regimes with improved thermal and aerodynamic performance and to develop technical solutions aimed at reducing the environmental impact of coal-fired boilers.

Although coal's share of global electricity generation will decline, it will remain the dominant fuel in Kazakhstan's thermal power industry in the coming decades. For this reason, one of the key challenges facing energy policy and the power industry in Kazakhstan is to develop cleaner technologies for coal-fired plants and bring them into practical use. Suppressing pollutant formation and cutting total emissions deserve particular attention here [12–17].

Methods

The numerical framework combines physical and physicochemical submodels to resolve heat and mass transport in a high-temperature reacting multiphase environment. The governing formulation consists of the three-dimensional Navier–Stokes equations and multistage reaction processes [18, 19]. The main equations used to solve the problem are given below.

Law of conservation of mass (continuity equation):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0, \quad (1)$$

Law of conservation of momentum (Navier-Stokes equation):

$$\frac{\partial(\rho u_i)}{\partial t} = -\frac{\partial}{\partial x_j}(\rho u_i u_j) + \frac{\partial \tau_{ij}}{\partial x_j} + \frac{\partial P}{\partial x_i} + \rho F_i, \quad (2)$$

where ρ is density, $u_{i,j}$ is velocity in the direction*i, j,* $x_{i,j}$ is Cartesian coordinates, $\tau_{i,j}$ is viscous stress tensor, P is pressure, F_i is external forces.

Law of conservation of energy (first law of thermodynamics):

$$\frac{\partial}{\partial t}(\rho h) = \frac{\partial}{\partial x_i}(\rho u_i h) - \frac{\partial q_i^{res}}{\partial x_j} + \frac{\partial P}{\partial t} + u_i \frac{\partial P}{\partial x_i} + \tau_{ij} \frac{\partial u_i}{\partial x_i} + S_h, \quad (3)$$

where h is specific enthalpy, q_i^{res} associated with the transfer of energy through thermal conductivity, flow of matter and diffusion, S_h is energy source through chemical reactions and radiant heat exchange.

Law of conservation of components of a mixture:

$$\frac{\partial}{\partial t}(\rho C_\beta) = -\frac{\partial}{\partial x_i}(\rho C_\beta u_i) + \frac{\partial j_i}{\partial x_i} + S_\beta, \quad (4)$$

where C_β is mass concentration of the component β, j_i is average mass flow in the i-th direction, S_β is source term of the component β.

The gaseous phase is treated in an Eulerian framework for the calculation of momentum, energy, and species transport. Within the Eulerian formulation, local conservation equations are solved for mixture mass, momentum, enthalpy, and the concentrations of gas-phase components. A Lagrangian approach is used to describe the motion and heat and mass transfer of individual fuel particles along their trajectories. Turbulence closure is provided by a two-equation k – ε model, in which k denotes turbulent kinetic energy and ε represents its dissipation. Radiative heat transfer is represented by a six-flux transfer model [20-21].

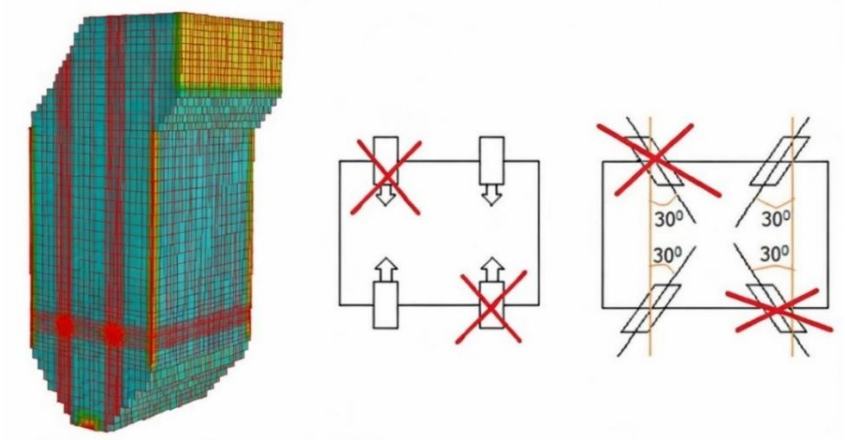
The given system of equations (1-4) is solved numerically using modern methods of computer 3-D modeling. Formation of combustion products in the pulverized-coal flame is calculated with a chemical-kinetic scheme applicable over the temperature and reactant-concentration ranges encountered in the furnace. However, detailed modeling of all ongoing reactions (including all intermediate reactions) is only possible in simple cases, such as carbon monoxide combustion, due to high computational costs or a lack of information on all intermediate reactions.

Physical statement of the problem and computing mesh

The computational experiment is designed for the parameters of the boiler of the Barnaul Boiler Plant, which operates at a Thermal Power Plant in the city of Shakhtinsk in the Karaganda region of Kazakhstan. The BKZ-75 steam boiler is a vertical-tube unit with a capacity of 75 tons of steam per hour (heating power of 47 MW). The boiler is a single-drum, natural-circulation boiler with a U-shaped layout. Four axial-blade swirl burners provide pulverized-coal combustion in the BKZ-75 boiler. They occupy one burner level, with a pair installed on the front furnace wall and a pair on the rear wall [22].

Karaganda coal of the KR-200 grade is used as the main fuel with the following characteristics: ash content A_r = 35.1%, volatile matter yield V_{daf} = 22%, moisture content W_r = 10.6%, net calorific value Q_i = 18.55 MJ/kg.

Figure 2 presents the computational domain of the BKZ-75 furnace divided into control volumes (a), together with the burner arrangement used for the emergency operating cases (b, c). The burners taken out of operation are indicated in red.



a) b) c)

Figure 2 – Division of the furnace computational domain into control volumes (a) and burner configurations used in the simulations: (b, c)

Two fuel–air supply configurations were considered for the simulated emergency operating condition. A straight-flow arrangement was used in the first case, where two of the four burners kept running and the other two were switched off (Figure 2b). The second case retained the same pair of working burners but organized them for swirling flow: a prescribed swirl was imposed on the air stream and the burner jets were inclined at 30° toward the boiler symmetry axis, the two remaining burners again being out of service (Figure 2c).

For both emergency configurations, the numerical calculations provided the spatial distributions of the velocity vector, temperature, and NO_2 concentration throughout the furnace chamber and at the outlet. These data were subsequently used to compare the aerodynamic and thermal behavior of the two pulverized-coal combustion regimes.

Results and discussion

Figure 3 shows the distribution of the total velocity vector in longitudinal sections (x = 3.0 m) of the combustion chamber during emergency operation for the direct-flow and vortex fuel-air mixture delivery methods. In both cases the flow field reaches its peak velocities in the burner region, that is, within the active combustion zone. Downstream of it the flow splits: one fraction turns down toward the cold funnel and forms a recirculation zone with vortex structures, and the rest rises toward the furnace outlet.

Figure 3 indicates that introducing swirl into the fuel–air stream enhances heat and mass transfer within the reacting two-phase flow. The improvement is associated with the development of a stable, strongly turbulent recirculating structure, which increases mixing intensity and results in a more uniform combustion environment. In contrast, the straight-through method is characterized by a less organized flow structure, reduced turbulence, and lower mixing efficiency.

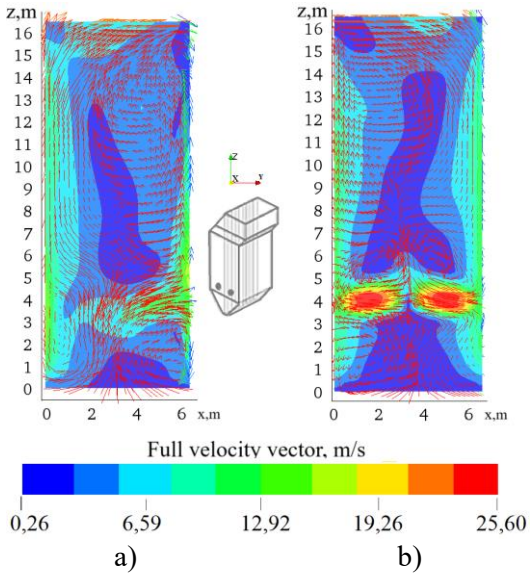


Figure 3 – Distribution of velocity vectors in the longitudinal plane (x = 3.0 m) of the BKZ-75 boiler furnace under emergency operating conditions: (a) straight-flow fuel–air supply and (b) swirling fuel–air supply

Figure 4 presents the velocity-vector field at the furnace outlet cross-section (h = 16.75 m) for the two fuel–air supply configurations considered under emergency operating conditions. As the turbulent stream approaches the furnace outlet, the velocity field becomes progressively more uniform, while the strength of the vortical structures weakens and the gas velocity decreases accordingly.

This phenomenon reflects the natural decay of turbulence and the stabilization of flow at the chamber exit, ensuring smoother and more predictable gas movement. In the vortex feed mode, the observed lower outlet velocity is primarily a result of enhanced mixing and increased energy dissipation within the highly turbulent vortex structures. These swirling flows significantly improve heat and mass transfer, diminish temperature gradients, and enhance the overall homogeneity of the combustion process. As a result, the vortex method provides more stable and efficient combustion even during emergency shutdowns, outperforming the straight-through configuration in terms of uniformity of flow, thermal distribution, and operational reliability. The findings clearly emphasize the benefits of vortex-based mixing in managing combustion dynamics under critical operating conditions.

Figure 5 presents the two-dimensional distribution of the cross-sectionally averaged temperature along the height of the BKZ-75 furnace for the two-emergency fuel–air supply configurations, namely straight-flow and swirling modes. The numerical results indicate that the introduction of swirl broadens the high-temperature region, while the gas temperature at the furnace outlet becomes lower. The local minimum observed in the temperature profiles is associated with the injection of a comparatively cold air–fuel mixture through the burner level located at approximately (z=4 m). The predicted outlet temperatures are in satisfactory agreement with experimental measurements reported for the combined heat and power plant [23] and with the corresponding theoretical estimates obtained using the thermal calculation procedure developed by the Central Boiler-and-Turbine Institute (NPO CKTI) [24].

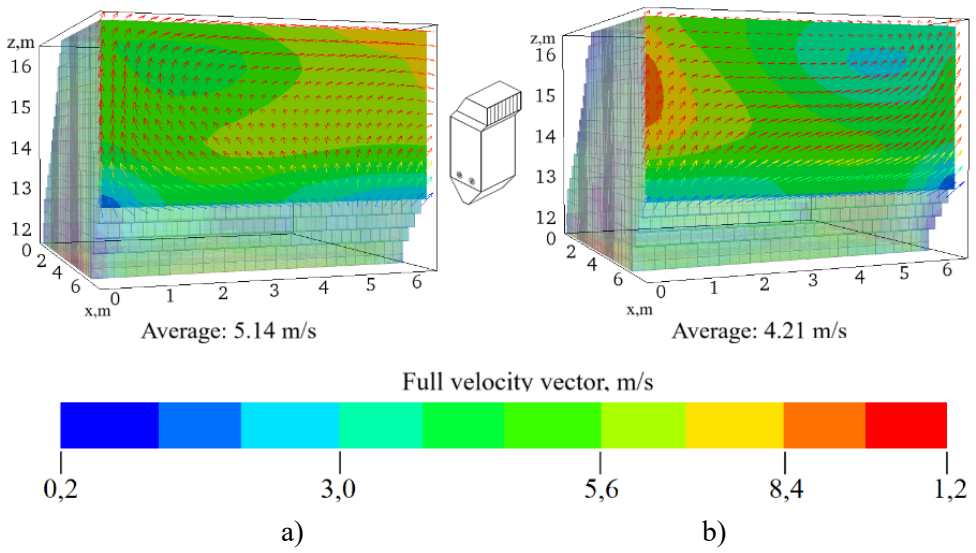


Figure 4 – Distribution of the full velocity vector in cross sections at the outlet (h=16.75 m) from the combustion chamber of the BKZ-75 boiler in emergency mode: (a) direct-flow and (b) vortex method of air-fuel mixture supply

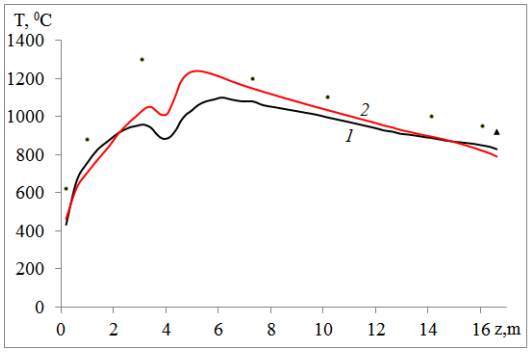


Figure 5 – Distribution of temperature (T) along the height of the combustion chamber of the BKZ-75 boiler in emergency operating conditions: 1 – direct-flow method of air-fuel mixture supply; 2 – vortex method of air-fuel mixture supply; ● experimental data at TPPs [23]; ▲ - is theoretical values obtained by the method of thermal calculation (NPO CKTI) [24]

Figure 6 presents the spatial distribution of O_2 concentration in the central region of the BKZ-75 furnace under emergency operating conditions for the two fuel–air supply configurations considered in the study.In the direct-flow supply scheme (Figure 6a), a pronounced spatial unevenness in oxygen distribution is observed. The area with reduced O_2 content is concentrated in a relatively small region at the bottom of the combustion chamber, while zones with higher oxygen concentrations are located near the upper part of the chamber. This distribution indicates insufficient mixing of the fuel-air mixture and the formation of a gravity-driven layered flow structure with limited vertical interaction. Such stratification can result in local fuel-rich pockets, incomplete combustion, and the generation of pollutants, including CO and unburned hydrocarbons. Additionally, localized overheating may occur, potentially compromising boiler reliability and operational safety.

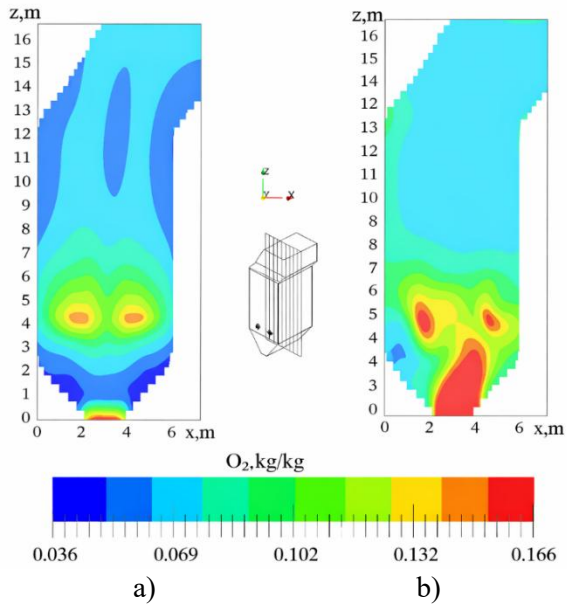


Figure 6 – Distribution of oxygen concentration O_2 in the central section (y = 3.3 m) of the combustion chamber of the BKZ-75 boiler in emergency mode: (a) direct-flow and (b) vortex fuel and air mixture supply method

In contrast, the vortex feed method (Figure 6b) produces a significantly more complex and dynamic

distribution pattern. The oxygen concentration field exhibits alternating regions of low and high O_2 throughout the central zone, indicating enhanced turbulent mixing and more effective vertical penetration of reagents. Compared to the direct-flow scheme, the vortex method reduces regions with critically low oxygen levels and distributes O_2 more evenly across the combustion chamber height. The rotational motion inherent to the vortex feed promotes a symmetrical flow field, mitigates stable stratification, and supports more complete combustion, leading to higher thermal efficiency and lower emission of incomplete combustion products.

Taken together, the results point to the mixture supply method as a decisive factor for the aerodynamics of the combustion chamber, for mixing efficiency, and for performance as a whole. The vortex feed regime, in particular, promotes the formation of a well-mixed and stable flow pattern, ensuring more uniform oxygen distribution throughout the combustion chamber. Improved mixing accelerates the interaction between the reactants, limits the development of locally fuel-rich regions, and lowers the probability of incomplete combustion. As a result, the process becomes thermally more efficient and remains more stable over the operating range. Furthermore, by mitigating stratification and supporting more complete oxidation, the vortex method helps lower emissions of carbon monoxide and unburned hydrocarbons. The observed results demonstrate the importance of air-fuel supply configuration to combustion performance, particularly during emergency and transient regimes, in which rapid and uniform mixing is required to support safe, efficient, and environmentally responsible operation.

Figure 7 shows the three- and two-dimensional NO_2 concentration fields along the furnace height *h*for the BKZ-75 boiler under emergency operating conditions, comparing the two fuel–air supply configurations considered in the simulations.

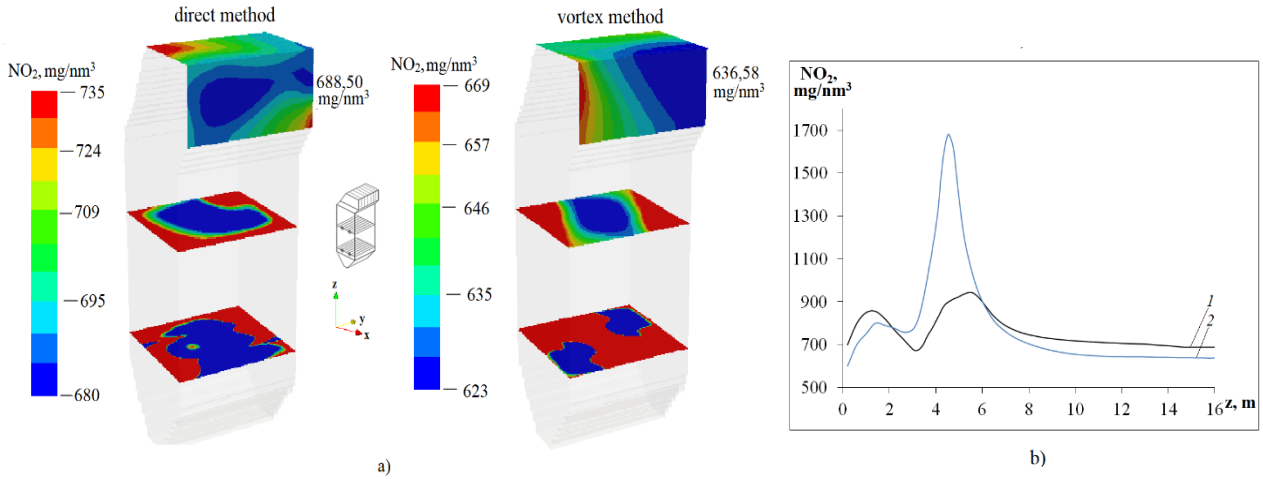


Figure 7 – Nitrogen dioxide concentration NO_2 versus the height h of the BKZ-75 boiler combustion chamber in emergency mode, given in three-dimensional (a) and two-dimensional (b) form: curve 1 – direct-flow supply of the fuel and air mixture, curve 2 – vortex supply

As the data show, the cross-sectional average NO_2 concentration attains its maximum where burning is most intense, namely in the burner zone. The two-phase flow there is heated to about 1240°C, and such conditions strongly favor nitrogen oxide formation via the thermal and prompt mechanisms alike. The elevated temperature enhances the reaction rates between molecular nitrogen (N_2) and oxygen (O_2), while the presence of hydrocarbon radicals in the flame front further accelerates NO production. A portion of this NO is subsequently oxidized to NO_2, resulting in a clearly defined peak in NO_2 concentration at this height.

As the combustion products rise through the chamber, the temperature gradually decreases, and the local oxygen availability is dynamically altered by the ongoing combustion reactions and flow patterns, resulting in a gradual decline in NO_2 concentration. In the upper regions of the combustion chamber, lower temperatures reduce the rates of both thermal and prompt NO formation, while the continued mixing with cooler combustion gases further dilutes NO_2 levels. At the outlet of the chamber, the average NO_2 concentration reaches its minimum, reflecting the combined effects of gas dilution, decreased reaction rates, and partial recombination or reduction of nitrogen oxides in cooler zones. This overall vertical distribution is clearly illustrated by curves 1–2 in

Figure 7b and highlights the strong dependence of NO_2 formation on local thermal and chemical conditions.

The trends obtained tie the NO_2 maxima to areas of high temperature and vigorous combustion, while concentrations drop in colder parts of the furnace where the reacting flow is less active. Understanding this spatial variation is essential for optimizing fuel-air mixing, combustion efficiency, and emission control strategies. Under emergency and transient operating conditions, temperature variations and changes in the flow structure become more pronounced. A detailed description of the NO_2 distribution is therefore important for adjusting burner operation, controlling the air supply, and selecting appropriate emission-reduction measures. The observed decrease in NO_2 concentration can be attributed to several contributing factors. First, the temperature of the gas environment drops significantly with increasing altitude, which leads to a decrease in the rates of reactions responsible for NO_x formation. Second, the concentrations of active nitrogen-containing components of the fuel and oxidizer decrease, since most of them have already entered into combustion reactions in the lower zone. Third, the upper part of the furnace contains mainly cooled and chemically stabilized combustion products, in which NO_2 formation virtually ceases. Thus, NO_2 concentration profiles are characterized by a pronounced maximum in the active combustion zone and a subsequent decrease towards the chamber outlet.

A comparison of the two air–fuel mixture supply configurations shows that the cross-sectional average NO_2 concentration at the combustion chamber outlet decreases from 688.50 to 636.58 mg/Nm³ when the direct-flow system is replaced by the vortex system. The reduction amounts to approximately 8%, as indicated by the profiles corresponding to curves 1 and 2 in Figures 7(a) and 7(b).

Conclusion

Numerical simulations were performed for the BKZ-75 boiler under emergency operating conditions, considering two fuel–air supply arrangements: straight-flow and swirling modes. Attention in this study was given to the velocity and temperature fields and to how pollutant concentrations are distributed in space inside the furnace. The way the fuel–air mixture is delivered proved to have a marked influence on furnace aerodynamics, on heat and mass transfer, and on where high-intensity combustion regions develop.

The direct-flow mode is characterized by the formation of layered, stratified flows with limited vertical mixing and localized temperature and concentration peaks, which reduces combustion efficiency and contributes to localized increases in nitrogen oxide emissions. The vortex method of feeding the mixture creates stable, highly turbulent vortex structures that ensure intensive mixing of the reactants, equalization of temperature and velocity fields, and combustion stabilization throughout the entire chamber height.

The NO_2 field indicates that the highest concentrations occur in the active burner region. This area corresponds to the zone of greatest combustion intensity. With the swirling configuration, the NO_2 concentration at the furnace outlet decreases by about 8% compared with the straight-flow case. This reduction indicates more favorable emission performance. The effect is mainly associated with stronger mixing and a more uniform thermal field, which limit local temperature peaks and reduce conditions favorable to pollutant formation. Overall, the numerical results show that swirl-based fuel–air delivery improves combustion uniformity and stability while intensifying heat and mass transfer. Under emergency operating conditions, NO_x emissions are significantly reduced.

The data obtained can serve as a basis for optimizing burner design and fuel supply systems of BKZ-75 boilers at coal-fired combined heat and power plants. Introducing vortex-based mixing offers gains in both operational and environmental performance, making boiler operation under critical conditions safer, more reliable, and cleaner in terms of emissions.

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A.S.Askarova: supervision, methodology,. **S.A.Bolegenova**: conceptualization, funding acquisition. **A.O. Nugymanova**: investigation, writing – original draft preparation, writing reviewing and editing. **V. Yu. Maximov**: resources, software. **S.A. Bolegenova**: investigation, data curation, visualization. **S.A. Umarov**: software, validation.

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