Low-NOx Firing Systems with Swirl Burners Installed on Boilers PK-39-IIM and BKZ-420-140-5

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The paper presents basic technical solutions for the firing system and design of the burners of boilers PK-39-IIM and BKZ-420-140-5 when firing Ekibastuz coal. The developed low-NOx firing systems ensure low nitrogen oxide emissions both at low cross-section heat release rates and high furnace cross-section heat release rates. Technical solutions developed for the firing systems are based on the simulation of coal combustion in furnaces of the mentioned boilers using ANSYS Fluent software.

Keywords: low-NOx firing system, nitrogen oxides, NOx, Ekibastuz coal, boiler PK-39, boiler BKZ-420, CFD-simulation.

1. Introduction

Until recently, environmentally friendly combustion of solid fuel in boilers did not seem to be of great importance. Major focus was on stable ignition and combustion, as well as complete fuel burnout; therefore, combustion systems were based on the excess air on the main burners $\alpha_{bur} \geq 1.0$ and at the furnace outlet $\alpha_f'' = 1.2$, high swirl rates in fuel-air mixture nozzles (n = 1.6-2.0), inadequate staged combustion inside the furnace and the best possible and quick mixing of air with fuel. All this made it possible to ensure low level of unburned carbon at the boiler outlet, while resulting in a great amount of nitrogen oxides formation. However, at the moment, strict requirements related to environmental performance call for the development of new technical solutions for low-NOx firing systems and burners. The use of 3D multivariate CFD-simulation of firing processes enables not only accurately checking of technical solutions adopted, but also analysis of the impact of many factors on stability of combustion and NOx emissions at the design stage without costly full-scale experiments. Verification involving full-scale experiments proves the objectivity of selected models and parameters.

2. Main technical solutions for firing systems and burner design

The developed low-NOx firing systems and burner designs were developed primarily to meet NOx emission requirements, while maintaining the required boiler efficiency. This can be achieved through the use of new approaches to the arrangement of combustion processes in the furnace. First, excess air at the main burners is reduced ($\alpha_{bur}<1.0$) through partial air removal from the main burners. Second, swirl burners design is improved, so that horizontally-staged fuel combustion is achieved. Upgrading of burners involves changed swirl parameter in the air-fuel nozzle, amended velocity conditions in a burner, as well as installation of dedicated elements in air-fuel nozzles - turbulators. Thus, both vertically and horizontally staged types of combustion are realized in the furnace. At the same time, there is no impact on combustion stability and boiler performance.

Developed technical solutions for the combustion system of boiler PK-39-IIM with high furnace cross-section heat release rate to reduce NOx emissions include the following:

- Reduction of primary air portion in the main burners through installation of pulverized coal classifiers downstream of the mills;
- Vertically staged combustion which is ensured through two-stage combustion of Ekibastuz coal with an opposite-fired two-level arrangement of swirl burners operating at low excess air $\alpha_{bur}<0.75$;
- Horizontally staged combustion which is ensured through the installation of new swirl burners with a reduced speed rates for air-coal mixture, and low-swirl flow.

Developed technical solutions for boiler BKZ-420-140-5 with low cross-section heat release rate for the combustion system include the following:

- Installation of the main opposed-fired swirl burners into one level at $\alpha_{bur}\approx0.93\div0.98$;
- Installation of special splitters-turbulators in air-coal nozzles;
- Vertically staged combustion due to OFA;
- Horizontally staged combustion, which is ensured due to unique design of the air-coal nozzles, availability of a non-flow channel separating streams of air-coal mixture and secondary air streams, as well as through dividing secondary air into two streams with different swirling parameters.

3. Computational simulation of coal combustion processes in the furnace

3.1. Problem description

To check the adopted technical solutions, firing process simulation was carried out for the refurbished boilers PK-39-IIM and BKZ-420-140-5 using ANSYS Fluent software. For this purpose a geometric model was built.

This geometric model was covered with a computational grid (Fig. 1). For more accurate calculation of parameters in the area of large gradients of reactant concentrations and velocities (zone of mixing and high-intensity combustion), computational mesh was made finer using a larger number of final elements – meshes. Scope of platen and convective surfaces in the computational model was specified as porous medium with resistance factors. Inside these banks a constant volume factor of heat pickup was specified which ensured lower temperature of gas flow when it passed through the surface by the value determined based on the boiler thermal design.

Computational model uses the following assumptions:

- Air inflow to the furnace is via a sloping bottom, and in the areas of interfaces between the sloping bottom and LRS, and interfaces between LRS and MRS;
- Selected coefficient of heat-transfer from a furnace wall to heated medium, temperature of agent in the walls along the furnace height within the range 370-440°C, and wall emissivity – 0.8 correspond to wall efficiency factor ψ=0.35;

– Pulverized-coal/air mixture and air were evenly supplied on cross-sections of the appropriate nozzles.

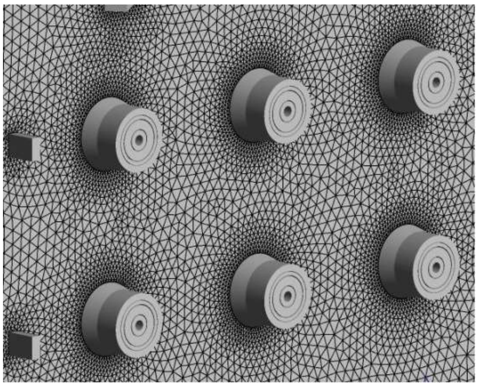


Figure 1. Computational grid near the burners.

3.2. Mathematical model

To calculate turbulence flows in the boiler furnace, ANSYS Fluent software numerically solves continuity and momentum equations, Reynolds-averaged, stationary made, to close which a standard κ-ε model of turbulence is used. To describe the motion and heat-and-mass transfer of single fuel particles along their trajectory, Lagrange approach is used. For simulation of radiant heat transfer exchange, P-1 model was used [2,3].

Fraction composition in the fuel is described using Rozin-Rammler distribution, where typical solid particle size δ_o depends on fuel grinding fineness (R_{90}) and polydispersity index. In the thermal balance of a coal particle the following is taken into consideration: heat of water evaporation, heat transfer through thermal conductivity and convection, radiant heat transfer and char combustion heat. The temperature of a particle is assumed to be the same inside a particle, this temperature, however, differs from the temperature of a gaseous environment.

ANSYS Fluent enables simulation of thermal, prompt and fuel oxides formation, as well as the processes of their reduction.

3.3. Verification of mathematical model and NOx formation model

This mathematical model and NOx formation model were verified using computer simulation of an operation option with conventional burners and existing firing systems [4]. With the adopted kinetic constants of combustion of Ekibastuz coal coke, as well as the accepted combustion scheme $C \rightarrow CO \rightarrow CO_2$, the adopted mathematical model showed good convergence with operational data in terms of unburned carbon and CO emissions. Chosen model of NOx formation also demonstrates satisfactory convergence with the test results (Table 1).

		Averaged experimental data	Computer simulation
Unburned carbon	q_4, %	2.5	2.8
CO concentration	C_{CO}, mg/Nm3	29	35
NOx concentration	C_{NOx}, mg/Nm^3	611	598

Table 1. Comparison of operation data with the results of computer simulation.

3.4. Results

The paper presents the results of a 3D simulation of the in-furnace processes for boiler body PK-39-IIM and boiler body BKZ-420-140-5 at a 100% load and with 4 mills in operation with the technical solutions suggested.

Figures 2-5 show the results of a computational simulation for firing processes in boiler PK-39-IIM as the temperature fields, NOx concentration, and discrete phase concentration.

Due to low excess air on the burners and low swirl of the stream in air-fuel mixture nozzles in the burner paraxial zone, the fuel is in an oxygen-free zone, which ensures the availability of nitrogen oxides reducing zone within this area. At that, the burner operation is stable, with a well-developed reverse-flow area and inflow of hot flue gases to the burner throat. Ignition and combustion of Ekibastuz coal are stable. The flame uniformly fills the furnace space. The developed firing system for boiler PK-39-IIM ensures reliable performance of the boiler throughout 0.6-1.0D_{nom} load range. It is worth mentioning that for the boilers commissioned in 2008-2013, the design level and achieved NOx level was ~ 600 mg/Nm^3, and for the new boilers with a modified firing system and burner design upon their commissioning, improvements in environmental, technical and economic performance are expected. At a nominal load under base-load conditions with 4 operating mills, design level of reduced nitrogen oxides concentration on the level of 530 mg/Nm^3 and unburned carbon ≤ 2% are ensured. Thus, it is possible to say that in the furnaces with high cross-section heat release rate the technical solutions suggested related to low-NOx firing system design allow the engineers to receive nitrogen oxides level ~10-15% lower than the required 600 mg/Nm^3 level, which confirms their environmental friendliness.

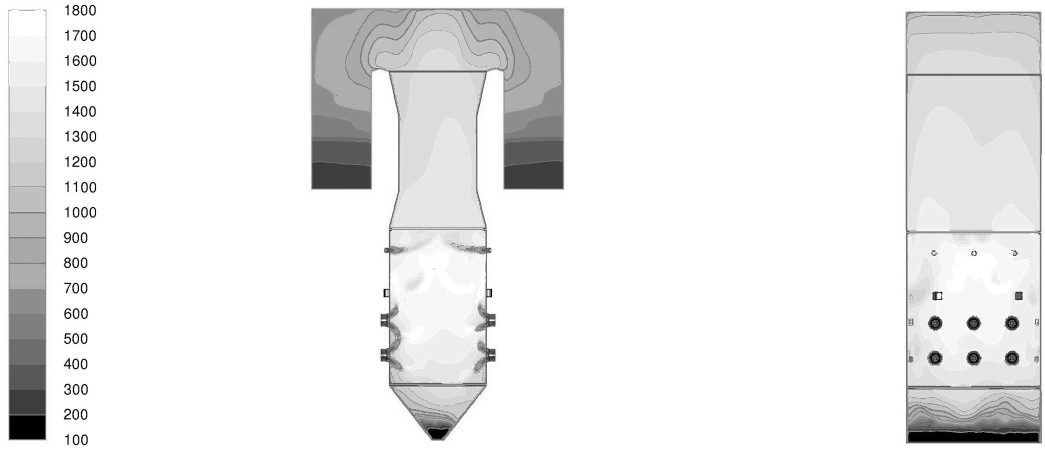


Figure 2. Temperature fields in the boiler axial sections, °C

Figure 3. Temperature fields, °C, in the sections on the level of:
a) 1st burner tier; b) 2nd burner tier

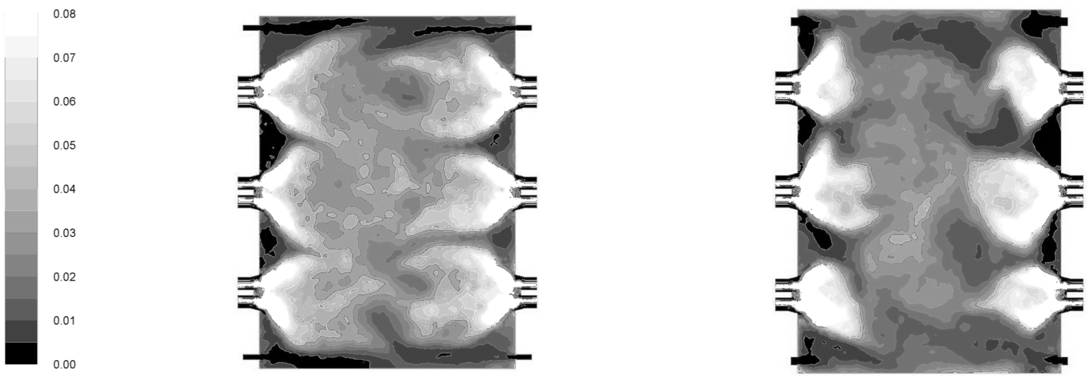


Figure 4. Field of concentration of a discrete (solid) phase, kg/m3, in the sections on the level of:
a) 1st burner tier; b) 2nd burner tier

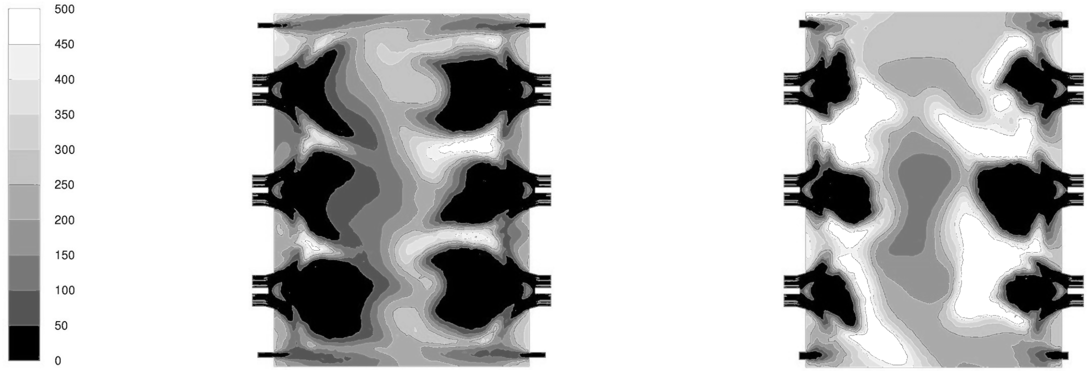


Figure 5. Field of NO_x concentration, ppm, in the sections on the level of:
a) 1st burner tier; b) 2nd burner tier

Figures 6-9 show the results of a computational simulation for firing processes in boiler BKZ-420-140-5 as the temperature fields and discrete phase concentration.

The design of air-coal nozzles provides for the installation of special technological elements (splitters-turbulators) placed at the outlet part of the nozzles around the circumference. Thanks to these splitters-turbulators highly-concentrated jets of air-coal-air mixture are formed (Fig. 12), which facilitates more rapid heating of these jets (highly-concentrated PC jets) at the burner outlet, intensive emission of volatile matter and its ignition in low excess air environment. Swirler blades make pulverized coal concentration on the walls of splitters-turbulators higher. This design of flow path of air-coal nozzles of the burner significantly reduces fuel NOx generation. Burner design also makes use of a two-stage fuel combustion within the limits of the flame of each individual burner (horizontally staged combustion). Secondary air is divided into two flows with different swirling parameters. Internal flow is swirled and it promotes flame stabilization. Outer channel has a higher swirling parameter, and part of the air breaks away from the main dust flow at the initial part of the flame in the area where volatiles are emitted and ignited. Low flow channel which divides the air-fuel and secondary air nozzles also contributes to this process.

Figure 6. Temperature fields along the furnace axes, in a vertical section along the axis of central burners and on the burner tier, °C.

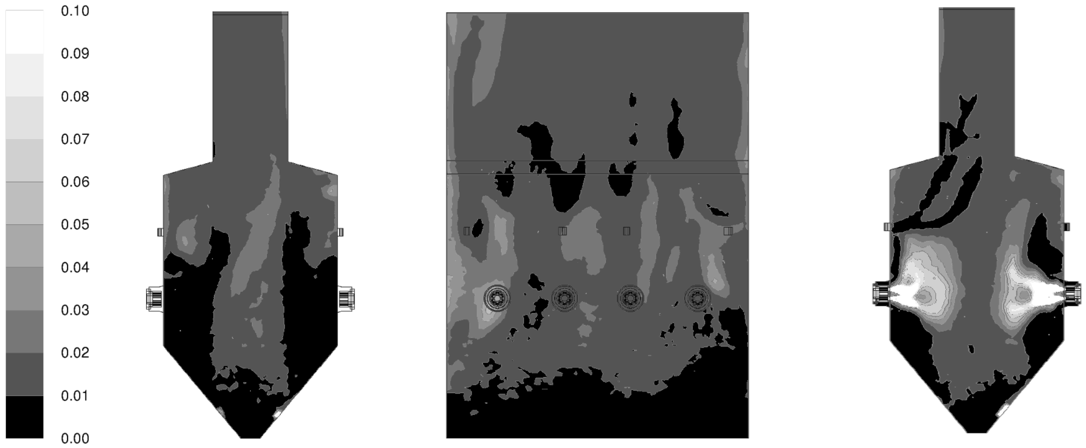
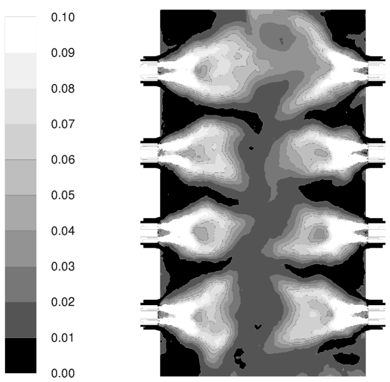


Figure 7. Concentration of discrete phase along the furnace axes and in a vertical section along the axis of central burners, kg/m^3.



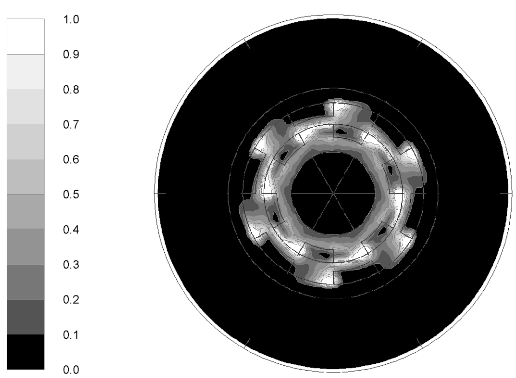


Figure 8. Concentration of

Figure 9. Field of discrete phase

discrete phase at the burner tier level, kg/m^3.	concentration at the burner outlet, kg/m^3.

For boilers BKZ-420-140-5 firing Ekibastuz coals the developed technical solutions make it possible to provide the level of formation of nitrogen oxides in the amount of 500-550 mg/Nm^3, while unburned carbon at the boiler outlet is not more than 2%, which is confirmed by operating conditions under which the level of nitrogen oxides formation is 420-500 mg/Nm^3 [6,7]. Thus, the developed technical solutions make it possible to ensure an even lower level of nitrogen oxides for the furnaces with a low ross-section heat release rate.

4. Conclusions

Thanks to computational simulation, technical solutions for the right choice of a firing system and burner design were checked and improved. Based on a 3D simulation of firing processes for boiler PK-39-IIM, it was shown that nitrogen oxide concentrations in the furnaces with high heat release rates could be at a level of 530 mg/Nm^3 (under normal conditions, O2 = 6%). For boiler BKZ-420-140-5 furnaces with low heat release rates, it was shown that nitrogen oxide concentrations could be at a level of NO_x=420-500 mg/Nm^3 (under normal conditions, O2 = 6%).

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