Numerical simulation of fuel staged swirl combustion in the invert furnace of boiler on advanced ultra-supercritical steam parameters

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Abstract. The paper considers the schemes of Kuznetsky lean coal combustion for the M-shaped boiler. With such a boiler profile, it is possible to significantly reduce the length of main steamlines, which is especially important for the advanced ultra-supercritical parameters of the superheated steam. The furnace in this boiler unit is performed downward (invert). In this work, the aerodynamics of 6 combustion schemes was simulated by means of computational fluid dynamics. All considered schemes were designed on the basis of direct-flow burners and nozzles. For the most aerodynamically reasonable scheme the thermal processes in the boiler furnace firing Kuznetsky lean coal have been simulated by means of computational hydrodynamics. The simulation results showed a high efficiency of fuel burnout: loss due to unburned combustible equaled 0.1%, carbon-in-ash loss equaled 0.8%. Carbon monoxide concentration at the furnace outlet in conversion to excess air equal $\alpha = 1.4$ amounted 226 mg/m$^3$, the nitrogen oxides concentration in the flue gases (in conversion to normal conditions) equaled 424 mg/m$^3$. It is appropriate to use the results obtained in this research in the development of new solid fuels combustion schemes.

1. Introduction

Increasing of steam initial parameters up to advanced ultra-supercritical parameters (AUSP) in the thermodynamic Rankine cycle is one of the promising ways to improve its efficiency [1]. USKP power plant units include units with main steam temperature of 700-760°C and pressure above 35 MPa. The main factor limiting the implementation of this technology in practical terms is the high cost of alloys the main steamlines should be made of. In order to reduce the length of the main steamlines, we proposed an M-type boiler profile (figure 1) [2]. In this boiler the superheater outlet headers are located at the turbine level, while turbine traditional location maintains and the combustion chamber is performed downward (invert).

In addition, the boiler is designed to combust Kuznetsky lean coal, which is low-reactive (with a volatiles content to the dry ash-free mass equal 16.6%). To ensure stable ignition and efficient combustion of such coals, it is conventionally used to arrange liquid slag removal in the furnace, which in turn leads to significant nitrogen oxides emission (often exceeding 1000 mg/m$^3$). Thus, in order to meet the increasingly stringent environmental requirements for nitrogen oxide emissions, combustion should be organized in a furnace with dry ash removal. This circumstance imposes increased requirements on the combustion scheme of this coal.
Commonly, solid fuel carbon-in-ash loss and nitrogen oxides emission are inversely related, i.e. with a decrease in carbon-in-ash loss, the concentration of nitrogen oxides in flue gases increases. Therefore, the combustion scheme must meet the optimal balance of these specified parameters. Present work is devoted to the searching for the optimal fuel combustion scheme for the described boiler.

2. Description of the research object
The proposed boiler is designed to operate in a power plant unit with a 500 MW steam turbine. The boiler is of once-through type, with intermediate steam reheater and dry ash removal. The nominal steam-rated capacity is 1320 t/h. The superheated steam pressure equal 36 MPa, the temperatures of main steam and reheated steam are 710°C. Flue gases after the furnace turn into inclined upward gas ducts, where the semi-radiation (platen) and convective surfaces of the steam superheater and steam reheater are located. Further, the flue gases enter the downward convection shafts, where the economizer heating surfaces are located (there is also a convective steam reheater in the right shaft).

Burners are arranged on the front and back walls of the furnace in its upper part. In the lower part of the furnace, the front and back waterwalls have inclination at an angle of 55°, forming an ash hopper. The boiler pulverized-coal system is closed loop, with 8 ring-roll pulverizers and hot air drying of fuel. The furnace is designed for combusting coal with a lower calorific value of 25.75 MJ/kg, moisture content of 7% (to the as-received mass), and ash content of 16.9%. The estimated fuel consumption at the rated boiler load is equal 145.4 t/h with a gross boiler efficiency of 91.8%.

3. Selection of optimal burners and nozzles arrangement
It was decided to develop the combustion scheme on the basis of direct-flow burners and nozzles. Their main advantage is the possibility of organizing the desired aerodynamics in the combustion zone due to the interaction of direct-flow jets in the furnace volume. Six combustion schemes were developed and investigated in total in this work. Figure 2 shows as an example the arrangement of
burners and nozzles for the first developed combustion scheme. All schemes are based on the following principles:

- The arrangement of direct-flow burners and nozzles is counter-displaced. In each plane of burners location there is the same set of burners and nozzles, but the direction in the next nearby plane is reversed in opposite side.
- Arrangement of burners and nozzles in each vertical plane is performed in such a way that 2 vertical swirls are formed, rotating in opposite directions.
- A staged air supply to the combustion zone is organized, which ensures the suppression of the nitrogen oxides formation.
- Maximum recirculation of hot flue gases to the roots of the burner jets.
- Excess air in the burner jets is assumed to be as low as possible.

![Figure 2. Burners and nozzles arrangement in combustion scheme №1 (to the left – arrangement in vertical plane, to the right – in horizontal plane).](image)

PA&F1, PA&F2 – primary air and fuel burners of 1st and 2nd levels; SA1, SA2 – secondary air nozzles of 1 and 2 levels; TA – tertiary air nozzles.

In combustion scheme №1, all burners and nozzles channels are rectangular ducts, burners PA&F1 and PA&F2 are mounted at an angle of 20° upward, air nozzles SA1, SA2 and TAN are normal to the furnace walls. The detailed description of all combustion schemes and simulation results are presented in [3]. In this work, we concentrate on the obtained results and investigate in more details the best of considered schemes.

The study of each scheme was carried out by the numerical simulation in the ANSYS Fluent software package [4]. The simulation was performed not for a full-scale furnace but for its physical bench model (scale of 1:45, made of plexiglass). The physical model was isothermal and allows to study the furnace aerodynamics by blowing air. Jets visualization was obtained by red-hot sawdust entering to the physical bench volume through the burner and nozzle channels.

At the first stage, the combustion scheme №1 (figure 2) was studied by the physical modeling and numerical simulation. And these qualitative results were compared with each other to verify the numerical model adopted in ANSYS Fluent. A qualitative comparison (figure 3) showed a jet trajectories good coincidence, so the same models and settings were used for the numerical study of the remaining combustion schemes as for the combustion scheme №1.
Figure 3. Qualitative comparison of the physical modeling results (a) and numerical simulation results (b) for the combustion scheme №1.

The Navier-Stokes equation, the continuity equation, and 2 turbulence equations were used in numerical model of furnace aerodynamics. The k-ε Realizable model and the Standard wall function were used as a turbulence model. A stationary problem was solved in a three-dimensional case. Simulation results analysis of the of the first scheme showed that it is generally operable, but has several disadvantages: direct contact with the burner jets of the opposite furnace walls, weak swirl flows of the lower level burners jets (figure 3). To eliminate these disadvantages, five more combustion schemes were developed. The best aerodynamics was obtained in the combustion scheme №6 (figure 4).

Figure 4. Numerical simulation results of the aerodynamics of the combustion scheme №6
a) the burners and nozzles arrangement; b) the velocity vectors in the burner №4 longitudinal section, m/s; c) velocity vectors in the horizontal section at a high 0.5 m above the burners PA&F2.

There are swirl flows in the upper and lower (less intense) levels of the burners in the vertical plane (figure 4b). The vortices also visible between the counter-displaced planes of the burners and nozzles in the horizontal plane. All this indicates an intensive mass transfer in the active combustion zone and should lead to high combustion efficiency. No zones with direct contact of the burner jets with the
furnace walls were found. Therefore, it was decided to continue further research on scheme №6, as the most optimal. A physical isothermal model (bench installation) was made for this scheme and a combustion process numerical simulation was performed.

4. Fuel combustion numerical simulation

The purpose of fuel combustion numerical simulation was to check the main furnace parameters, characterizing the efficiency, ecological safety and reliability of its operation: the degree of fuel burnout, the distribution of flue gas temperatures along the height and in horizontal sections, the flue gas components concentration along the height of the furnace (O₂, CO and NO). Obtaining information about these values by other methods, except for numerical simulation, meets significant difficulties. So for a new designed boiler installation this method actually has no alternatives.

Combustion numerical simulation was also performed in the ANSYS Fluent software package, which has proven itself well in solving problems of this type. It is necessary to create a 3D model of the furnace estimated volume and a computational mesh before starting the simulation. The SolidWorks software package was used for creation a 3D model (figure 5a). Then the 3D model was imported into the ANSYS ICEM program, where the computational mesh was created (figure 5b). The mesh was made of tetrahedra with 2 layers of prisms in the boundary wall layer to account for the laminar viscous layer. The total number of cells in the mesh was 3,940,757.

![3D model of furnace](image1)

![Surface mesh](image2)

Figure 5. The estimated furnace volume for numerical simulation of combustion scheme №6

- a) furnace 3D model;
- b) surface mesh of the furnace walls, burners and nozzles.

The accepted numerical model of the furnace includes the following equations system [5]: the continuity equation; the energy conservation equation; the Navier-Stokes equation; the transport equations for chemical reagents and reaction products (diffusion equations); the radiative transport equation; the state equations; the discrete phase equations.

A Realizable k–ε model of turbulence was used with a Scalable wall function. The problem of fuel particle motion was solved using the Discrete Phase Model (DPM) with the law of friction between particles and gas Spherical. The rate of devolatilization was described using the Single Kinetic Rate model. For the coke burnout model The Kinetic/Diffusion Surface Reaction Rate model was used. The mechanism of coke combustion is adopted as a two-staged: in the first carbon is oxidized to carbon monoxide CO and then CO is oxidized to CO₂ by a homogeneous reaction. The evaporation of coal dust moisture in the furnace in this model was not taken into account due to the insignificant moisture
content of this coal type. The combustion rate of gaseous combustible components is assumed according to the kinetic-diffusion model Finite-Rate/Eddy-Dissipation. The transfer of thermal energy by radiation is assumed according to the Discrete Ordinates (DO) model. The nitrogen monoxide NO formation includes three types of them: thermal, prompt and fuel. The thermal NO formation is assumed by the Zeldovich mechanism and the fast NOx formation by the Fenimore mechanism. The degree of fuel nitrogen to NO conversion is assumed to be equal 20%.

The boundary conditions at the inlet for the drying agent and hot air were set by mass flow rates. The fuel consumption was calculated from the heat balance of the boiler and was also set in the model by the mass flow rate. The boundary conditions on the walls were set as mixed. The boundary condition at the model outputs was set as zero static pressure (Pressure-outlet). The size range of coal dust particles is calculated on the basis of the rest on a sieve with a size of 90 µm R90, adopted from the range recommended in [6] for ring-roll pulverizers (R90 = 14%).

The calculation was carried out until the values of residuals for the continuity equation did not reach the order of 10^{-3}, for the energy equation the order of 10^{-6}, and the mass flow rates unbalance of the model reached about 10^{-2} kg/s and the total energy unbalance of the model about 10^{4} W. In addition, the temperature of the gases at the furnace outlets and the amount of burnt coke in the volume of the furnace were monitored as additional convergence criteria. The required convergence was achieved after performing 6000 iterations.

The visualization of the numerical simulation results is shown in figures 6-8. The obtained results indicate a high degree of fuel burnup, which is untypical for lean bituminous coals with dry ash removal: carbon-in-ash loss of the fuel amounted to q4 = 0.8%. Loss due to unburned combustible q3≈0.1% was determined from the CO concentration at the furnace outlet. The standards in our country recommend for lean bituminous coals keeping q4 losses not higher than 2% for dry ash removal and not higher than 1.5% for liquid slag removal [7].

The distribution of temperatures in the furnace (figure 6) shows that the maximum temperature is located at the lower burners level and equal to 1751 °C. Temperatures in the longitudinal (figure 6b) and horizontal (figure 6c) sections are evenly distributed, there are no locations with direct contact of flame with the furnace walls. This indicates that the burner’s number and pitch were chosen correctly. The flue gas temperature at the furnace outlet (in front of the platen surfaces) was 1256 °C, which should exclude the platen heating surfaces slagging.

Analysis of the velocity vectors in the furnace (figure 7) confirmed the qualitative picture of the jet flow obtained by the numerical and physical modeling of aerodynamics on an isothermal test bench. An intense vortex formation in the horizontal plane could be noted in figure 7c. The figure illustrates significant masses of gases ejected by PA&F2 jets, which favorably affects fuel ignition.

Figure 6. The furnace temperature fields for combustion scheme №6
a) in the longitudinal section of burner №4; b) in the central cross section of the furnace; c) in a horizontal section at the level of the SA2 nozzles.
The furnace outlet content of carbon monoxide according to the results of numerical modeling was 226 mg/m³, with a standard value of 400 mg/m³. Despite the fulfillment of the normative values, such a concentration leads to the appearance of loss due to unburned combustible at the level of \( q_3 = 0.1\% \).

The graph in figure 8 shows a monotonic decrease in CO concentration with a decrease in the level of the furnace, while there is a local peak in concentration at the level of the burners PA&F2.

![Figure 7. Velocity vectors in the furnace for combustion scheme №6](image)

a) in the longitudinal section of burner №4; b) in the longitudinal section of burner №5; c) in a horizontal section at the level of the burners PA&F2.

Based on the calculation results, the \( \text{NO}_x \) concentration is equal 424 mg/m³. The standard values of \( \text{NO}_x \) concentrations in flue gases are established in [8] and amount to 350 mg/m³. Therefore, only the primary methods provided are not enough for \( \text{NO}_x \) suppression in the furnace. In this regard, the selective non-catalytic reduction is recommended for this boiler to provide nitrogen oxides reducing in the flue gases. The graph in figure 8 shows the change in the concentration of nitrogen monoxide along the furnace height. The NO concentration has a minimum at the PA&F1 level and increases monotonically until the end of the fuel afterburning (20 m level).

Additional verification of the numerical modeling results was carried out by qualitative comparing the trajectories of the jets with the results of physical modeling at the physical bench and by comparing the temperatures along the furnace height, obtained as a result of the thermal zone calculation according to the method [7]. Verification showed an acceptable coincidence which indicates the sufficient reliability of the results obtained.

![Figure 8. Changes in the horizontal sectional average concentrations of CO and NO along the furnace](image)
5. Conclusions

In the work a complex numerical study was carried out aimed at finding the optimal combustion scheme for lean coal in a descending invert furnace. At the first stage, 6 combustion schemes were developed and numerically investigated. An analysis of the qualitative patterns of the jets trajectories made it possible to choose one of the most aerodynamically successful scheme. Intense vortices were observed in the horizontal and vertical planes of this scheme, while there were no zones where the burner jets touched the furnace walls.

A numerical simulation of the fuel combustion was carried out for the most successful scheme. The simulation results showed a high efficiency of fuel burnup: loss due to unburned combustible amounted to 0.1%, carbon-in-ash loss were 0.8%. The outlet furnace content of carbon monoxide in conversion to excess air equal α = 1.4 was 226 mg/m³, the concentration of nitrogen oxides in the flue gases (in normal conditions) was 424 mg/m³. It is appropriate to use the results obtained in this research in the development of new solid fuels combustion schemes.

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