The use of numerical simulation to determine the coal combustion efficiency in the A-USC boiler

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Abstract. In this paper, numerical simulation of coal combustion in the invert furnace of a boiler for a 500 MW power unit designed to operate on advanced ultra-supercritical steam parameters (A-USC) is performed. The use of A-USC technology makes it possible to reduce fuel costs for electricity production compared to steam turbine units of previous generations. Also it influences to reduce the level of emissions of harmful substances into the atmosphere. Modeling of the invert furnace at the nominal boiler load was carried out for the developed direct-flow burners and nozzles arrangement of burning coal. After numerical simulation the results were obtained and made it possible to analyze the furnace aerodynamics and the temperature distribution inside the furnace volume. The calculation of the indicators of efficiency and environmental friendliness was carried out and their values appeared smaller than regulatory permissions, which allows us to recommend the developed burners arrangement scheme for its use in invert furnaces. The furnace operation simulation at reduced loads of 70% and 50% was carried out and the results showed the reliability of the developed combustion scheme.

1 Introduction

The concentration of 15.2% of all world coal reserves on the territory of the Russian Federation makes it possible to actively develop coal-fired electric power industry. By 2022, the capacity of coal-fired power plants in Russia amounted to 41,770 MW and Russian Federation is in sixth place in the ranking of countries producing electricity by burning coal. Today Russian coal generation has the following features: heterogeneous distribution of solid fuel power plants across the country; low efficiency of condensing pulverized coal power units; high average age of power equipment; low rates of development of new coal generation.

In this regard, the relevance of this work is due to the need to update the fleet of power plants of the Russian Federation operating on solid fuel through the construction of new power units with an increase in steam parameters and the use of modern world achievements in the construction and operation of power units.

The use of the coal power units with main steam parameters 700-760 °C and more than 35 MPa (advanced ultra–supercritical parameters A-USC) allows to achieve the highest efficiency for electricity generation among all existing categories of steam turbine thermal power plants on solid fuel. At the moment, extensive research has been carried out in foreign and Russian scientific organizations on this technology on the following topics: development of the power unit thermal scheme [1-4], selection of materials and experimental study of their properties under operating conditions of high-temperature boiler and turbine surfaces [5, 2], various concepts formulation of the boiler and turbine arrangement [6], evaluation of the possibility of using traditional and developing non-standard layouts of steam boilers [2, 7, 8, 9, 10, 11]. A feature of some A-USC boilers layouts is an invert furnace to minimize the main steam pipelines lengths due to the high price of the material from which they should be made (nickel alloys). There are no detailed studies on the development of methods for burning coal in furnaces of this configuration, since it is most often assumed to use vortex burners in a typical angular or counter arrangement for foreign boilers [2, 8, 9, 12]. The possibility of using direct-flow burners for A-USC boilers is considered in detail in relation to the horizontal boiler furnace. The possibilities of using this type of burners for invert furnaces are described in the works of researchers from the Research Institute "MPEI" [13, 14], however, there are no detailed studies of coal combustion schemes in an invert furnace. Thus, the development of a solid fuel combustion scheme of burners and nozzles arrangement in an invert furnace for advanced ultra-supercritical steam parameters is an important task.

This article discusses the final stage of a scheme for burning coal in an invert furnace development. The combustion scheme was developed earlier using a simplified numerical model [15]. Using numerical simulation of the coal combustion process in the furnace, the evaluation of the efficiency and

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environmental friendliness of the scheme is carried out. A developed combustion scheme in an invert furnace is shown in Figures 1 and 2.

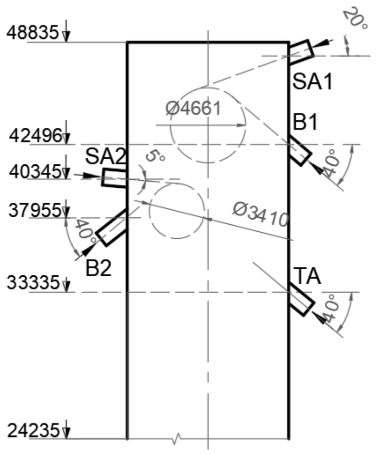

Fig. 1. Arrangement of burners and nozzles in a vertical plane in an odd section.

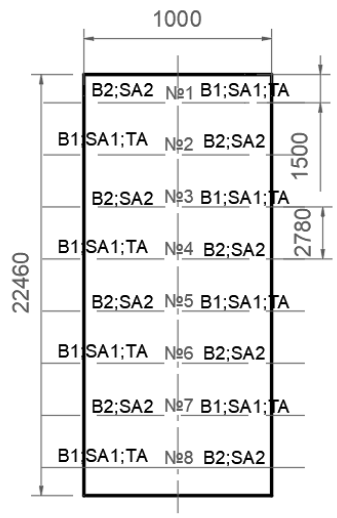

Fig. 2. Location of burners and nozzles in the top view.

The developed scheme for burning coal for a 500 MW boiler has a two-level arrangement of direct-flow burners according to a counter-offset scheme. The upper level burners (B1) and the lower level burners (B2) are made with a tilt at an angle of 40° up with respect to the horizontal plane. The secondary air inlet (SA1 and SA2) is made at an angle of 20° and 5° down, respectively. Tertiary air is supplied to the furnace lower part at an angle of 40 degrees upwards. All nozzles and burners have a rectangular cross-section. There are flow dividers on all upper level burners B1, with the exception of the extreme burner located next to the side walls. In total there are 8 sections in the scheme, alternating with each other with a mirror arrangement of burners and air nozzles on opposite walls (counter and offset scheme).

2 Computation details

Hard coal burning process numerical simulation was performed in the ANSYS program. The main characteristics of hard coal are given in Table 1.

Table 1. The main characteristics of Kuznetsky TR brand coal.

Parameter	Value
The lower heating value, kcal/kg	6150
Devolatilization value, %	16.6
Humidity (per working weight), %	7
Ash content (per working weight), %	16.92
Sulfur content (per working weight), %	0.23
Carbon content (per working weight), %	68.62
Hydrogen content (per working weight), %	3.35
Oxygen content (per working weight), %	2.13
Nitrogen content (per working weight), %	1.75

The paper uses a numerical model for which validation was performed on the K-50-250 boiler installed at the heating boiler-house of Tashtagol town and running on coal. A detailed description of the validation process is given in [16].

2.1 Mesh generation

The creation of the investigated furnace 3D model at a scale of 1:1 in the CAD program was performed. The calculated 3D model was created with geometric simplifications that did not affect the flow and heat transfer processes of interest. The burners and nozzles were modeled by planes whose cross sections corresponded to specific burners/nozzles cross section.

Using the ICEM ANSYS mesh generator, the 3D model is filled with a calculated mesh. The choice of the cells optimal number was made based on the results of a mesh study. For this purpose, the meshes were created: coarse, medium, fine (the elements number is 1.6, 3, 5.5 million, respectively). Calculations were performed for each mesh. Then the average values were taken in several horizontal planes: the values of flow velocities and temperatures. The values of these parameters were found using the Richardson extrapolation [17, 18] for an infinite number of mesh elements and their comparison with the values obtained for different mesh was performed. Based on the mesh study results the mesh with 3 million elements was selected for further calculations.

2.2 Numerical models

The ANSYS Fluent software package presents a wide variety of mathematical models that allow to simulate furnace processes in sufficient detail.

The program solves conservation equations for all flows types (mass and momentum, energy and mixture components) and also uses various empirical models that are selected by the researcher depending on the cases.

The flue gases flow and solid particles was modeled using the Euler-Lagrange system: the Navier-Stokes motion equations (Euler's approach) were used to describe the motion of a continuous fluid, and the coal dust particles motion (discrete phase) was calculated using the Lagrangian approach.

The Realizable k-ε model [19] is used to resolve turbulent processes, which closes the Reynolds averaged Navier-Stokes equations (RANS) in the turbulence theory. The heat transfer simulation in a continuous and discrete phase was performed using the energy conservation equation and the heat balance equation for particles. The Discrete Ordinates (DO) model was used [20, 21] to resolve heat exchange due to radiation. The value of the local emission coefficient of triatomic gases H_2O and CO2 was calculated using the The Weighted Sum of Gray Gases Model.

Several stages of coal dust combustion were simulated: a particle heating with subsequent moisture release, evolution of volatiles, volatile burning, char burning. The evolution of volatiles was calculated using a single-step reaction-based simple model. The kinetics/diffusion-limited rate model [22] was used to determine the surface reaction rate. The volatile burning (gas phase) was described by two-stage reactions: the initial oxidation of volatile occurs, and then the reaction of CO with oxygen is carried out. The reactions rate in the gas phase in addition to chemical kinetics was determined by the presence of turbulent processes using the finite rate/eddy dissipation model [23, 24].

The simulation of the thermal, fuel and promt nitrogen oxides formation was carried out after the completion of the fuel combustion process simulation based on data on temperatures, turbulence, velocities and concentrations of reaction products in the furnace volume.

2.3 Simulated cases and boundary condition

Variant calculations were carried out at nominal 100% and at reduced loads of 70% and 50% for a complete assessment of the efficiency of the developed coal combustion scheme in an invert furnace.

For reduced loading additional preliminary calculations of the dust preparation system were performed and the excess air was recalculated. The fuel consumption and excess air are shown in Table 2.

Table 2. Fuel consumption values and excess air at different boiler loads.

Parameter	Boiler load		
	100%	**70%**	**50%**
Total fuel consumption per boiler, kg/s	41.22	28.85	20.78
Excess air at the furnace outlet	1.2	1.2	1.4
Air infiltration the furnace	0.02	0.014	0.01
Total excess primary air	0.219	0.223	0.225
Excess air for the secondary air nozzles SA1	0.2	0.2	0.242
Excess air for the secondary air nozzles SA2	0.32	0.321	0.388
Excess air for the tertiary air nozzles TR	0.441	0.442	0.535

The type of boundary condition "mass flow inlet" was used for burners and nozzles: the flow rates of the continuous fluid, the direction, mass flow, temperature, and chemical composition of the incoming flow were set. The interaction of the discrete phase with the input planes and the emission coefficient were taken into account. The furnace walls were modeled using the "wall" boundary condition type, where the wall temperature, the interaction of the discrete phase with the wall and the coefficients of radiant heat transfer were taken into account. The model has the outlet of all streams, which was taken into account using pressure outlet. To simulate the entry of coal dust into the burners injection settings were used, where velocities, flow rates, directions and particle diameter distribution after grinding in the mill were set.

Numerical values of mass flow rates and temperatures for setting boundary conditions are given in Table 3.

Table 3. Air parameters at the boiler inlet.

Burner/Nozzle	Total mass flow rate, kg/s	Temperature, °C
B1 and B2 (upper and lower level burners)	83.7	115
SA1 (the secondary air nozzle of the upper level)	73.9	350
SA2 (the secondary air nozzle of the lower level)	118.1	
TA (tertiary air nozzle)	162.8	

3 Results and discussion

3.1 Coal combustion simulation results in the inverted furnace at nominal load

To analyze the results of the calculation, the following ways of presenting information were used: vector fields, contour fields, particle trajectories, XY-type graphs. Figure 3 shows contour temperature fields in horizontal and vertical planes.

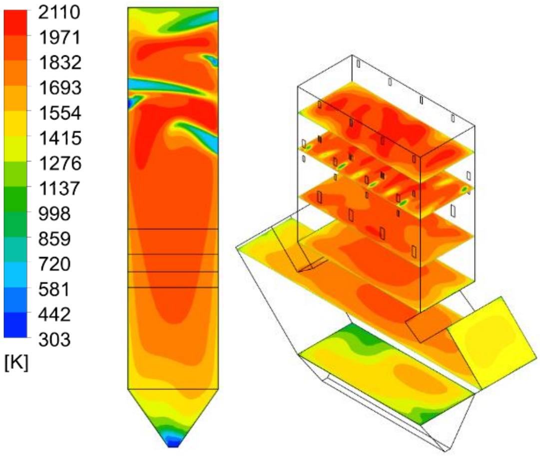

Fig. 3. Contour temperature field based on the numerical simulation results of coal combustion in an inverted furnace using the developed combustion scheme.

The graphical results show that with such burners and nozzles arrangement, two high-temperature zones are organized, in which the combustion of solid fuel occurs almost independently of each other. In the upper part of the furnace the burner B1 jets interact with the secondary air SA1 jets with a local excess air coefficient $\alpha < 1$, which leads to the almost complete absence of the nitrogen oxides formation in this zone. The SA2 jets prevent the penetration of the primary air jets from the lower level burners B2 and carry them into its flow. Further, jets of tertiary air prevent the movement of burner jets to the opposite walls, organizing their turn in the opposite direction. The interaction of B2 jets with hot air coming from the SA2 and TA nozzles provides high values of coal dust burnout. The vast majority of nitrogen oxides were formed after the supply of tertiary air since this creates a zone with excess air.

The concentration of carbon monoxide CO at the furnace outlet was calculated at the condition of excess air coefficient $\alpha = 1.4$. This value was 199 mg/Nm^3 at the normative value of 400 mg/Nm^3 [25].

The total concentration of nitrogen oxides NO_x in terms of NO_2 was determined from the concentration of NO at the furnace outlet, obtained from the results of numerical simulation. The nitrogen oxides concentration value in flue gases at the condition of the excess air coefficient $\alpha = 1.4$ was 453 mg/Nm^3, which is 20% lower than the technological emission value of 570 mg/Nm^3 [25].

The calculated value of heat loss with mechanical underburning was 0.45%, which is eleven times less than the permissible level of this value of 5% [26]. It indicates a high completeness of fuel burnout.

The flue gas temperature at the furnace outlet was 1230°C. This value is lower than the temperature of the ash deformation beginning of Kuznetsk coal, which indicates an extremely low probability of waterwalls slagging.

3.2 Coal combustion in the inverted furnace numerical simulation results at reduced loads

Figures 4 and 5 show graphs of temperature and turbulence kinetic energy for three loads.

Table 4 shows the indicators of efficiency, environmental friendliness and reliability of the furnace with the arrangement of burners and nozzles in accordance with the developed scheme.

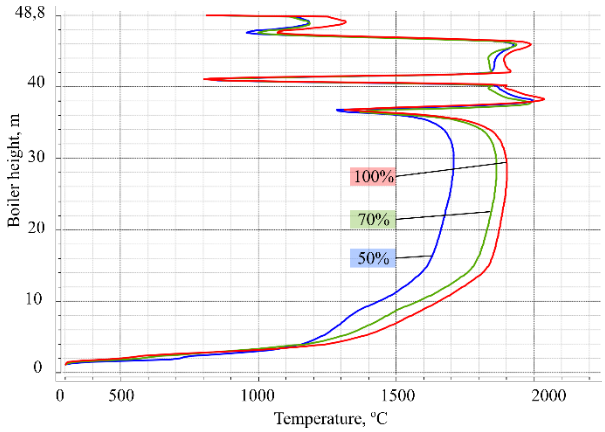

Fig. 4. Graphs of temperature dependence on the furnace height for various boiler loads.

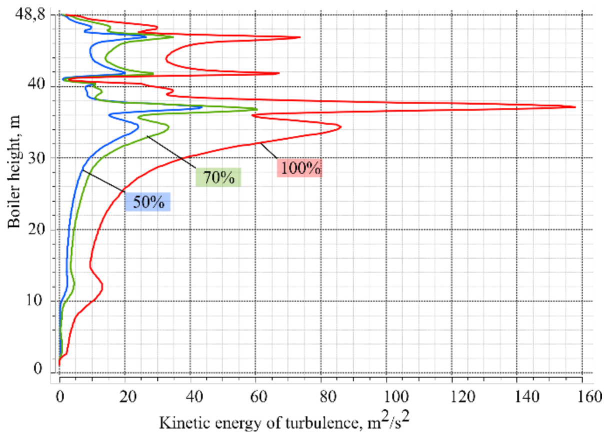

Fig. 5. Graphs of the turbulence kinetic energy dependence on the height of the furnace for various boiler loads.

Table 4. Indicators of efficiency, environmental friendliness and reliability of the furnace when using the developed combustion scheme at nominal and reduced loads.

Parameter	Boiler load		
	100%	**70%**	**50%**
Heat loss due to mechanical underburning of fuel, %	0.45	0.58	0.11
The carbon monoxide concentration at the furnace outlet, mg/Nm^3	199	125	40

Concentration of nitrogen oxides NOx at the furnace outlet, mg/Nm^3	453	227	140
Flue gas temperature at the furnace outlet, °C	1230	1162	1042
The amount of the produced carbon dioxide, g/kWh	745	514	374

Analysis of the results shows the reliability of the developed scheme. The pattern of intense vortex motion in the furnace volume remained the same as at the rated boiler load. The nature of the change in the turbulence kinetic energy along the furnace height, which characterizes the flow of turbulent processes at low loads, remained the same, with the exception of the numerical values of the energy, which is associated with the use of other values for the air flow rates supplied to the furnace.

Two high-temperature zones also remained where combustion processes take place at reduced loads: between the burners B1 and nozzles SA2; between the burners B2 and nozzles TA. This circumstance shows the independence of the torch location in the furnace volume on the load. The overall temperature level drops with decreasing load, which is associated with less heat generation in the combustion chamber. This is clearly seen in the graph of temperature dependence on the furnace height (Fig. 4). As the load decreases the temperature level decreases in the zones of intense combustion, which reduces the amount of thermal nitrogen oxides formation.

At 50% load an increased oxygen level was set corresponding to the excess air coefficient at the furnace outlet equal to 1.4, while at 100% and 70% loads this coefficient was 1.2. These measures were necessary to ensure maximum coal dust burnout.

The obtained indicators of efficiency, environmental friendliness and reliability of the developed combustion scheme confirm the correct air distribution over the burners and nozzles and its arrangement in the inverted furnace of the A-USC steam boiler burning coal dust. All parameters are smaller than normative and threshold values. When the boiler load is reduced the temperature level in the zones of intense combustion decreases, which leads to decreasing in the amount of thermal nitrogen oxides formation and significantly affects the level of total nitrogen oxides at the furnace outlet. The amount of generated carbon dioxide decreases in proportion to fuel consumption and is in the range for coal combustion technology for A-USC boilers (670–740 g/kWh).

4 Conclusion

To ensure the development of coal-fired power generation through the construction of new power units, a scheme was developed for lean Kuznetsk coal combustion using direct-flow burners and nozzles in an inverted furnace of an A-USC boiler. It will increase the power unit efficiency for the electricity production, as well as reduce the level of harmful substances emissions into the atmosphere. The scheme has a counter-offset arrangement of the direct-flow burners and air nozzles in two levels for organizing staged combustion and supplying tertiary air for fuel reburning. The developed scheme is aimed at the furnace operation with acceptable indicators of efficiency, environmental friendliness and reliability.

The numerical simulation of the coal combustion in an inverted furnace made it possible to calculate the furnace indicator, which are satisfactory: the heat loss with mechanical underburning is 0.45%, the total concentration of nitrogen oxides NO_x is 453 mg/Nm^3, the concentration of carbon monoxide CO at the furnace outlet is 199 mg/Nm^3, flue gas temperature at the furnace outlet is 1230°C. These values are smaller than the normative ones. Numerical simulation of the inverted furnace operation with the developed combustion scheme showed its performance at loads of 50 and 70%.

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