Enhancement of stability of ignition and burning of high-moisture coal in the furnace of the power boiler

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Abstract. The use of high-moisture coal with a moisture content Wr > 40% as fuel requires additional burning of a more expensive reactive fuel (gas or fuel oil support flaming), caused by the need to maintain a steady ignition and efficient burning of low-grade solid fuel. In this paper, a complex approach to the modernization of the technological scheme for the burning of Tulgansky brown coal (coal rank B1) with Wr ≥ 50% is proposed. It is supposed to improve the furnace aerodynamics, replace the pulverized-coal burners, perform refractory lining of water walls at the burner level, intensify the preliminary drying of the coal in the drying duct. Drying and burning of brown coal in the modernized scheme was studied by computer simulation in the software product ANSYS Fluent using boiler installation TP-14A as an example. The adequacy of the developed computer model was verified by comparing the results of numerical simulation with the results of full-scale tests and thermal calculations of the boiler TP-14A with the basic combustion scheme. The results of the simulation showed the possibility of stable burning of coal without gas support flaming. Reduction of fuel humidity before the mills was 4%, carbon-in-ash loss was 1.2%, concentration of nitrogen oxides in flue gases 300 mg/m³.

1. Introduction

The technology of pulverized coal combustion of high-moisture solid fuels has several distinctive features. First, the combustion process takes place at a low temperature in the core of the flame caused by a low calorific value of the fuel and the presence of a large amount of inert ballast (water vapor and drying agent) in the zone of active combustion (ZAC) [1]. Secondly, a significant part of the fuel heat is spent on evaporation of the remaining moisture of the coal dust in the furnace of the boiler and as a consequence, the stability of the ignition of the fuel reduces [2]. To maintain the stability of ignition of coal, additional expensive reactive liquid or gaseous fuels have to be burnt.

By now an extensive experience in burning this type of fuel has been accumulated in the world and a number of technological solutions to achieve their effective and sustainable combustion has been developed [2] - [4]. However, the proposed technical solutions have their own limits of use, i.e. allow to achieve the desired result not for all ranks of coals.

An illustration of the problem is the operation of boiler installations TP-14A on Tulgansky brown coal at Kumertauskaya CHP. To maintain sustainable ignition and incineration of Tulgansky brown
coal with a moisture content $W^r \geq 50\%$, combined use of natural gas as reactive fuel in the amount of 29-58\% is required.

In paper [5], the authors proposed an approach to the modernization of a furnace-burner system for increasing the efficiency of burning high-moisture coals and reducing the amount of gas support flaming. In this paper, variant of further improving of this combustion scheme and, in addition to the combustion chamber, a version of the preliminary drying duct retrofitting have been developed.

2. Object of study

In addition to the need for combined combustion of natural gas during operation of boilers TP-14A at Kumertau at CHP (figure 1) with this type of coal several problems were noted: increased carbon-in-ash loss with increasing of portion of coal in heat generation, low temperature of gases at the furnace outlet, exceeding the standard value of nitrogen oxides emissions into the atmosphere on loads close to the nominal, significant nonuniformity of heat and hydraulic characteristics in water walls and superheater. Coal dust is rather coarse $R_90 > 40\%$, so the furnace operation is characterized by the intensive dropping of a large particles in the ash hopper and an increased content of combustible in the slag. Additionally, burner jets exert dynamic pressure on the furnace rear water walls, which causes their intensive slagging.

![Figure 1. Scheme of the boiler installation TP-14A at Kumertau at CHP.](image)

1 - furnace; 2 – gas-intake duct; 3 - raw-coal storage hopper; 4 - pulverized-coal burner; 5 – pulverized-coal duct; 6 - raw-coal feeder; 7 – feed chute; 8 – blast box; 9 - separator; 10 – slag tank; 11 – pulverizing fan.
On the front wall of the furnace there are four dust-coal direct-flow burners with a capacity of 18 tons per hour for brown coal, on the side walls at a height mark of 10 meters there are four gas burners, two on each wall.

Table 1 shows the characteristics of the Tulgansky brown coal used at Kumertauskaya CHP. The humidity of coal $W_r$ is 52.2%, the total fraction of ballast $W_r + A_r$ is 68.7%, the calorific value $Q_i^r$ is equal to 7 MJ/kg. These characteristics indicate the extremely low quality of this coal, and the need for additional measures to maintain the stability of its ignition and combustion.

| Ash content $A_r$, % | Coal humidity $W_r$, % | Element mass fraction, % | Calorific value $Q_i^r$, MJ/kg | Volatile-matter yield $V_{DAF}$, % |
|----------------------|------------------------|---------------------------|-----------------------------|-----------------------------|
| 16.5                 | 52.2                   | 66.1                      | 6.6                         | 0.8                         | 26.2                       | 7.01                       | 65.2                       |

3. Upgraded technological scheme for burning Tulgansky brown coal

The problems of ensuring the stability of ignition, the efficiency of combustion, low emissions of nitrogen oxides and the increase in the convective component in the heat exchange of the boiler (increase in the temperature of the gases at the furnace outlet) are solved by the complex application of three measures: modernization of the coal preliminary drying system (mounting of the coal deceleration device in the drying duct), refractory lining of the part of the furnace water walls at the level of the pulverized-coal burners and optimization of the structure and arrangement of pulverized-coal burners and nozzles.

Refractory fire belt improves the ignition of the fuel, by reducing the heat absorption of the water walls in the ZAC and increases the temperature of the flue gas at the furnace outlet. The main function of the bottom air blowing in the technological scheme is to reduce the dropping of large particles into the slag tank and carbon-in-ash loss. The results of series of numerical studies given in [5] - [6] showed the most effective variant for installing bottom air nozzles on the walls of the slag tank on the same axis with pulverized-coal burners. A scheme of the boiler modernization is shown in figure 2.

Figure 2. Proposed variant of boiler installation upgrading.
a) Scheme of the proposed variant of upgraded furnace arrangement; b) longitudinal cross section of original solution of drying duct; c) cross section of retrofit variant with coal decelerating device.

1 - main burners; 2 - dump burners; 3 - bottom air nozzles; 4 - protective air nozzles; 5 - refractory fire belt; 6 - gas-intake ducts; 7 - fuel-air mixture channel; 8 - secondary air channel.

Fuel drying is an important stage in the preparation of solid fuels for combustion. For fuels with $W_r = 50\%$, about 15% of its calorific value is expended on evaporation of moisture. Therefore, it seems rational to modernize the preliminary drying device by installing a coal decelerating device inside the drying duct in the high gas temperature zone. The coal decelerating device is a hollow cone, which is located on the axis of the duct under the feed chute.

4. Description of the numerical model of the furnace

Investigation of Tulgan coal burnout was carried out by the numerical simulation method in the ANSYS Fluent software package. The mathematical model of the furnace includes the differential equations of conservation of mass, momentum, energy and diffusion equations, radiative energy transfer equation, equations of states as well. The gas environment was described as a continuous Euler phase, discrete particles were described in the Lagrange frame (DPM model). As a model of turbulence, a k-ε Realizable model with Standard Wall Function was used. The process of homogeneous burning of volatiles is specified by kinetic-diffusion Finite-Rate/Eddy Dissipation model.

The rate constants of volatile release and coke combustion were taken from [7] for grade A coal. Evaporation of moisture from coal dust into furnace and raw coal in a drying duct was described by the Wet Combustion model. As a radiation model, the P1 model was chosen, which is well combined in calculations with aerodynamics and convective heat transfer.

The boundary conditions of input flows (air, drying agent, fuel) were set by mass flow rates calculated from the heat balance of the boiler and the thermal calculation of the pulverized coal system. On furnace water walls were set the boundary conditions of mixed type, i.e. both radiative and radiant thermal perception are taken into account. For this, the steam saturation temperature in the water walls tubes is set to 314°C, the heat transfer coefficient from the tube walls is 38.5 kW / (m²·K), emissivity of the tubes varies depending on the operating mode in the range of 0.6 - 0.8.

At the first stage, the computer model was calibrated in ANSYS Fluent package and the selection of adequate settings for the processes of fuel combustion, heat transfer and the formation of nitrogen oxides was conducted. For this purpose, the boiler furnace TP-14A was simulated for the combusting scheme existing at Kumertauskaya CHP. The results of numerical simulation of the furnace in three modes of operation (100% load, 73% load and 50% load) were compared with TP-14A boiler test data and the results of thermal calculations of the furnace according to the normative method. The kinetic constants of devolatilization and organic matter combustion, emissivity of water wall tubes, and NO formation parameters were chosen in such a way as to achieve the smallest possible discrepancy with the test data.

The maximum discrepancy for carbon-in-ash loss was 21%, for nitrogen oxides concentration 11%, for carbon monoxide concentration 12%. The discrepancy with the thermal calculation of the temperature at the furnace outlet didn't exceed 30 °C. The obtained settings were used in the simulation of the modernized combustion scheme of the furnace.

The mesh sensitivity study was carried out for nominal operation mode. For this, the same version of the calculation was solved for meshes with an increasing number of cells, after which the obtained results were compared on the main indicators of the object of study and a conclusion was drawn about the stability of the calculated scheme and acceptable refinement of the grid. The grid is unstructured, contains tetrahedrons and in the near-wall area three layers of prismatic cells of 20 mm in size, were made. Based on the results of the calculations, it was concluded that the size of the grid with the number of 1 million cells provides the necessary accuracy of the calculation, and further grid refinement is unreasonable.
5. Results of numerical simulation of original and retrofitted technological schemes

Figure 3 presents the visualization of the results of numerical modelling of the drying duct for the original and retrofitted variants. There are four pulverized-coal systems in operation. Flue gases with a temperature of 805°C and a mass flow rate of 6.08 kg/s move to the drying duct from above. By the feed chute fuel particles with a flow rate of 5.75 kg/s and a temperature of 0°C under the action of gravity drop into the duct.

![Figure 3. Results of numerical simulation of preliminary drying process.](image)

The temperature field under the cone is significantly equalized in comparison with the original variant, which indicates more efficient heat transfer between gases and coal. As a result of the installation of the coal decelerating device, the temperature of the gases at the duct outlet is reduced by 30°C, the humidity of the fuel is reduced by 4%, which is equivalent to reducing the energy consumption for grinding within 7%. The decrease in the moisture content of the fuel was estimated as the difference in the mass flow rate of water vapour at the outlet and at the entrance to the model, the values of which are obtained in the ANSYS Fluent program.

Visualization of the results of numerical simulation of the retrofitted furnace is presented in figures 4-5. Carbon-in-ash loss in the retrofitted scheme equalled 1.2%. Carbon-in-ash loss was defined as the ratio of the heat of unburned coke to the boiler available heat, where the consumption of unburned coke was determined from the material balance of the coke residue in the ANSYS Fluent program.

![Figure 4. Gas temperature in the furnace chamber.](image)

The temperature at the furnace outlet is 1012 °C, which is almost 60°C higher than the corresponding value for the regime of co-combustion of gas and coal. The fraction of particles...
dropping into the slag tank (with specified value of fraction of bottom air equal to 0.12) turned out to be less than 1% of the total mass of the fuel, and the Carbon-in-ash loss of the dropped fuel were 0.1% (∼ 8% of the total carbon-in-ash loss).

Figure 4a illustrates the zone of active combustion, located approximately at the same furnace depth as in the original variant with gas support flaming, hence the ignition speed of Tulgansky coal in both cases are close. The maximum temperature of the gases in the furnace is 1450 °C, which in combination with the staged air supply to the furnace led to a reduction in nitrogen oxide emissions to 300 mg/m³ (by 12%). The concentration of nitrogen oxides was determined as the mass weighted averaged in the output plane of the model using the ANSYS Fluent program, after that it was recalculated to normal conditions for α = 1.4 (O₂=6%).

**Figure 5.** Visualization of the results of numerical simulation of the retrofitted furnace in cross-section of third coal-dust burner.

a) velocity vectors, m/s; b) mole fraction of O₂; c) mole fraction of H₂O; d) mole fraction of volatiles; e) mole fraction of carbon monoxide CO.

6. Conclusions
The results of numerical simulations of the proposed retrofit variant have shown the principal possibility of stable burning of brown coal from the Tulgan deposit without reactive fuel support flaming. Carbon-in-ash loss in the modernized scheme according to the simulation results amounted to 1.2%. The temperature at the furnace outlet increased by 60°C (1012°C), the fraction of carbon-in-ash loss of the large dropped particles decreased from 75 to 8%, the concentration of nitrogen oxides in flue gases decreased by 12 %. The coal decelerating device in the drying duct reduces the moisture content of the fuel in before the grinding mill by 4%, which saves 7% of electric energy for grinding.

Acknowledgement
The work was supported by the Russian Science Foundation (project №16-19-10463 of May 12, 2016).

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