Distinctive features of high-ash bituminous coals combustion with low milling fineness in furnace chambers with bottom blowing

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Abstract. Nowadays the problem of improvement of pulverized coal combustion schemes is an actual one for national power engineering, especially for combustion of coals with low milling fineness with significant portion of moisture or mineral impurities. In this case a big portion of inert material in the fuel may cause impairment of its ignition and combustion. In addition there are a lot of boiler installations on which nitrogen oxides emission exceeds standard values significantly. Decreasing of milling fineness is not without interest as a way of lowering an electric energy consumption for pulverization, which can reach 30% of power plant's auxiliary consumption of electricity. Development of a combustion scheme meeting the requirements both for effective coal burning and environmental measures (related to NOx emission) is a complex task and demands compromising between these two factors, because implementation of NOx control by combustion very often leads to rising of carbon-in-ash loss. However widespread occurrence of such modern research technique as computer modeling allows to conduct big amount of variants calculations of combustion schemes with low cost and find an optimum. This paper presents results of numerical research of combined schemes of coal combustion with high portion of inert material based on straight-flow burners and nozzles. Several distinctive features of furnace aerodynamics, heat transfer and combustion has been found. The combined scheme of high-ash bituminous coals combustion with low milling fineness, which allows effective combustion of pointed type of fuels with nitrogen oxides emission reduction has been proposed.

1. Introduction

Electric power consumption for coal pulverization is a significant proportion of the total consumption for balance-of-plant needs and may reach 30%. Combustion of high-ash coal is further complicated by the presence of ballast in the form of mineral impurities (Ap≥35%) and for its effective use requires a grinding fineness R90=15-20%. The specific electric power consumption for grinding is 25-35 kW·h/t. Another feature of using such types of coals is the need to provide a high temperature in the combustion zone in order to occur burnout with an acceptable carbon-in-ash loss. High temperatures and input of all the organized air into the combustion zone lead to NOx emission increasing.
For P-57 boilers operating on Ekibastuzsky coal (EC), the following parameters are typical for the design grinding fineness $R_{90}=15\%$: carbon-in-ash loss $q_{4}=1\div3\%$ with concentrations of nitrogen oxides $C_{\text{NOx}}=1000\div1500 \text{ mg/m}^3$ [1, 2]. The use of primary actions to suppress the formation of NOx allows reaching concentrations of $C_{\text{NOx}}\leq600 \text{ mg/m}^3$, with carbon-in-ash loss exceeding 2% [3-5]. The development of a combustion scheme that meets both the requirements for effective fuel burnout and environmental indicators (NOx emission) is an optimization task and requires a compromise between these two indicators.

The purpose of this research is developing such a scheme for high-ash EC combustion, which allows to increase the maximum permissible coarseness of grinding $R_{90}$ while keeping the carbon-in-ash losses $q_{4}$ at the same level (or decreasing) and further reducing formation of the NOx oxides. An analysis of researches carried out earlier [1-5] shows that the achievement of this goal is not possible without use of an integrated approach to the modernization of both the coal pulverization system and the furnace-burner devices.

The way of arranging the burners and air nozzles contains a huge potential in terms of increasing the efficiency of burnout of solid fuels. The application aspects of combined combustion schemes, in which, as a result of more optimal interaction between burner and air streams, complicated furnace aerodynamics is formed, are of current interest and require a thorough theoretical and experimental study.

This study includes numerical modeling of combined combustion schemes with various burner and nozzle design options, their arrangement and air distribution for burners and nozzles. The influence of the above factors on the main combustion parameters of EC was studied, including: carbon-in-ash losses, maximum temperature of gases in the furnace, outlet temperature of furnace, stability of aerodynamics, formation of NOx.

2. Description of the research object

The object of the study is the steam boiler P-57-3M (station №9) of the Troitskaya state regional power plant located in the Chelyabinsk region (figure 1).

![Figure 1. General view of the boiler P-57-3M Troitskaya state regional power plant](image)

1 - steam-to-steam heat exchanger; 2 - superheater wing walls; 3 - convective superheater; 4 - the second stage of the reheater; 5 - the first stage of the reheater; 6 - transition zone; 7 - economizer; 8 - hammer mill

The boiler is designed to work on high-ash EC in a unit with a 500 MW turbine. Boiler is a direct flow, with supercritical pressure, with steam reheating, single-hull, T-shaped, with balanced draft and dry-ash removal. Reserve fuel is fuel oil. The boiler has a coal pulverization system with coal-air mixture direct injection system comprising 8 hammer mills with centrifugal separators (four at a frontal and a back wall of the furnace). Above the mills there are bunkers of raw coal (BSU) with feeders (PSU), from which coal is passed by channel to the mills. To remove slag from the furnace there are 4 screw conveyors, the maximum capacity of each is 7.7 t/h. The auger bath is filled with...
water, into which the slag duct of the boiler is immersed to prevent air inflow in this part of the furnace.

3. Description of the developed variants of combined schemes

Modernization of the furnace-burners device is based on the following principles:
- combustion is organized on the basis of direct-flow burners and nozzles;
- arrangement of burners and nozzles according to the counter-shifted scheme;
- bottom air blast is used;
- staged combustion of fuel.

Based on these principles, 4 variants of combined schemes have been developed (figure 2). In each of the options, 2 tiers of pulverized-coal burners are retained, but their type is changed (replacing the vortex burners for direct-flow burners) and the arrangement. In each of the options, a bottom air blast is organized to reduce carbon-in-ash losses caused by particles dropping and a tertiary air blowing above the burners of the second tier. The constructions of pulverized-coal burners also differ in versions 1, 2 and 3 (in the schemes №3 and №4 the structures are the same).

The upper limit of the volume of the furnace corresponds to the level of 37 m, which corresponds to the beginning of the division walls in the modification of the P-57R boiler. The kinetic constants and the activation energy for the EC are taken from [6] as for coals of the C/D class.

4. Results of numerical simulation of combined schemes

Aspects of solid fuels burning in a system of direct-flow streams was considered in [7], where the main principles of the arrangement and design of the direct-flow burners are given. The idea of
increasing the perimeter of the ejection of burners for a P-57 boiler using combined scheme №1 as an example was described in [8] and [9]. Analysis of the results of variational numerical modeling for variants №1 and №2 shows that increase of the ejection perimeter of burner streams rises the rate of ignition and combustion of fuel, but the division of one stream on several (as in variant №1) weakens them. Divided streams are unstable in the horizontal plane, penetrate deep into the furnace badly and are pressed out to the walls. The flow of a stream from a large-diameter burner with a single stream (option №2) significantly increases its penetration deep into the furnace, but instability in the horizontal plane remains. As a result, the two opposing streams round each other instead of colliding.

Based on this, it is advisable to make all burners and nozzles as wide as possible to increase the stability of the streams in the horizontal plane (variants №3 and №4). In the schemes №3 and №4 the burners are made of rectangular cross-section with a width of 1200 mm, air nozzles with a width of 1000-1200 mm.

The results of the simulation show that the largest carbon-in-ash losses are attributed to the burners of the second tier (up to 80%). To reduce the proportion of fuel supplied to the burners of the second tier, it is necessary to equip the pulverized-coal pipe of each mill with dust splitters (Scheme №3) or by splitters-dust concentrators (Scheme №4). Such variants have already been applied for P-57 boilers and have improved the indicators, including NOx emission [4].

The best fuel burnout results were achieved in schemes №3 and №4 (q4=0.6-0.8 at R90=15% and q4=5-5.2% at R90=50%), worst in scheme №1 (q4=1.5-3.3 at R90=15% and q4>7% at R90=50%). Optimal for burnout efficiency and NOx formation is Scheme №4 (with projected grinding fineness qe=0.8%, CNOx=620 mg/m³). The minimum emissions of nitrogen oxides are achieved in the combined scheme №1 with a tertiary air fraction αtert=0.521 CNOx=278 mg/m³ at α=1.4, which meets the regulatory requirements. The maximum emissions correspond to scheme №3 - CNOx=733 mg/m³ at α=1.4.

The results of modeling of combined schemes with the best values of q4 losses for the projected fineness of grinding R90=15%, at the nominal load, with excess air at the outlet of the furnace α=1.2 and the primary air fraction α1=0.298 are summarized in table 1. In table 1, αb,b/αtert - the proportion of air in the nozzles of the bottom and tertiary blast respectively.

The large fuel concentration (80%) in the zone of the first tier burners in scheme №4 raises the heat liberation rate of this zone, but due to the vortex motion the maximum temperature of the torch is reduced in comparison with schemes №2 and №3. In addition, there is a decrease in the level of nitrogen oxides due to the organization of a three-stage combustion scheme (instead of two-stage in schemes №1-3). Temperature fields and velocity fields in the axial sections of the pulverized-coal burners are shown in figures 2 and 3.

| № | Parameter | Scheme №1 | Scheme №2 | Scheme №3 | Scheme №4 |
|---|-----------|-----------|-----------|-----------|-----------|
| 1 | Total perimeter of burners, m | 128.8 | 34 | 57.6 | 61.1 |
| 2 | Equivalent diameter of the coal-air mixture channel, m | 0.361 | 0.806 | 0.691 | 0.691 |
| 3 | Ratio of air excess αb,b/αtert | 0.182/0.57 | 0.082/0.33 | 0.15/0.343 | 0.15/0.103 |
| 4 | Output velocity of the coal-air mixture, m/s | 23.1 | 23.8 | 34.3 | 27 |
| 5 | Carbon-in-ash loss, % | 1.85 | 1 | 0.7 | 0.8 |
| 6 | Maximum flame temperature, °C | 1772 | 1858 | 1862 | 1807 |
| 7 | Temperature at the furnace outlet, °C | 1321 | 1303 | 1319 | 1275 |
| 8 | Concentration of NOx at α=1.4, mg/m³ | 463 | 632 | 733 | 620 |
5. Regression analysis of the results of numerical simulation

When developing a combustion scheme with complex combustion aerodynamics, it becomes necessary to predict the degree of burnout (or carbon-in-ash loss) with prescribed initial data: the geometry of the furnace, burners and nozzles; burners and nozzles arrangement; distribution of air and fuel between burners and nozzles. Such a task presents a challenge due to the complexity of the research object and the large number of variables affecting fuel burnup. In such a case, a reasonable step is to use methods of mathematical statistics, such as regression analysis. Regression analysis makes it possible to evaluate the influence of independent variables on the change in the objective function (carbon-in-ash loss $q_4$) statistically, without sufficient knowledge of the nature of this influence.

After selecting explaining variables for the regression function (in terms of significance and multicollinearity conditions), there are 8 factors: the equivalent diameter of the coal-air mixture channel $d_{eq}$, m; perimeter of the output section of the burner $P_{burn}$, m; output velocity of the coal-air mixture $\omega_1$, m/s; the proportion of primary air in the burner is $\alpha_{1burn}$; local air excess in the zone of active combustion (ZAC) $\alpha_{ZAC}$; the filling degree of the horizontal section of furnace by the lift part of the flame $\xi_f$; height of the complete combustion zone $h_{CCZ}$, m; grinding fineness $R_{90}$, %.

Figure 3. Temperature fields in the axial sections of combined schemes, °C

Figure 4. Velocity fields in axial sections of combined circuits
As a regression model, a power law was chosen, which showed the greatest coincidence with the results of the simulation. The coefficients of regression are found by the least squares method, the final forecast function looks like:

\[ q_4 = 70.1 \cdot a_{aq}^{-3.256} \cdot H_{burn}^{-1.176} \cdot a_{\phi}^{-0.774} \cdot a_{\phi_{CCZ}}^{1.087} \cdot \alpha_{ZAC}^{-2.275} \cdot \alpha_{\phi}^{-1.767} \cdot R_{CCZ}^{-1.176} \cdot R_{90}^{-1.579}, \]

(1)

This model is applicable to the prediction of \( q_4 \) of any combined scheme at the EC. Comparison of the values of \( q_4 \) obtained by the regression equation and by numerical simulation showed that for carbon-in-ash loss exceeding 0.5%, the relative error is about 15%, when \( q_4 < 0.5\% \) the relative error rises up to 30%.

6. Estimation of optimal grinding fineness

The most optimal variant is Scheme №4 allowing to burn Ekibastuzsky coal with carbon-in-ash loss \( q_4 = 0.8\% \) with residue on sieve 90 mic \( R_{90} = 15\% \) and \( q_4 = 5.2\% \) with residue \( R_{90} = 50\% \) at base load. The concentration of nitrogen oxides in the flue gases at \( \alpha = 1.4 \) is \( C_{NOx} = 620 \text{ mg/m}^3 \). To evaluate the optimal grinding fineness of this EA combustion scheme, a simulation of the variant for the P-57-3M boiler of the Troitskaya GRES was performed at different values of the fineness degree \( R_{90} \): 25%; 30%; 36%; 43% and 50%. Visualization of simulation results is shown in figure 5.

![Figure 5. Combined scheme №4 on the basis of the P-57-3M boiler of Troitskaya GRES](image-url)

a) temperature fields, K; b) concentration of O₂, kg/kg; c) trajectories of solid particles, (particle diam., m)

The simulation results were verified with the results of P-57 boiler of the Troitskaya GRES measurements. For an acceptable agreement of the values of carbon-in-ash loss \( q_4 \), the temperature at the furnace outlet and the concentration of NO the following parameters were changed: the activation energy of the devolatilization and char combustion, the water walls coefficient of thermal radiation, and the conversion fraction of fuel N that converts to intermediate species or NO. Changing of carbon-in-ash loss, the temperature at the furnace outlet and the concentration of NO\(_x\) at \( \alpha = 1.4 \) is illustrated in table 2.

| \( R_{90} \), % | \( q_4 \), % | \( T_\text{f} \), °C | \( C_{NOx} \), mg/m\(^3\) |
|-------|-------|-------|----------------|
| 25.3  | 1     | 1203  | 533            |
| 30    | 1.3   | 1198  | 531            |
| 36    | 1.8   | 1191  | 527            |
| 43    | 2.5   | 1180  | 526            |
| 50    | 3.5   | 1172  | 523            |
The economic grinding fineness \( R_{90\text{opt}} \) is considered to be the value of the residue on sieve 90 mic \( R_{90} \), which corresponds to the minimum total costs for coal grinding, repair of mill equipment and loss of unburned fuel. The costs of coal grinding and repair of milling parts were determined from the hammer mill capacity calculations. Figure 6 shows the dependence curve of the total cost from the grinding fineness.

Based on the results of the calculations, it was found that the minimum of the \( q_4 + A_{\text{grnd}} + A_{\text{repair}} \) curve corresponds to the optimum value of the residue on sieve 90 mic equal to \( R_{90\text{opt}} = 30.8\% \) (\( F_{\text{min}} = 83 \) rub/ton). This value coincides with the carbon-in-ash loss \( q_{4\text{opt}} = 1.4\% \), specific electricity consumption for grinding \( E_{\text{grnd}} = 20.6 \) kilowatt hour/ton.

![Figure 6. The economic grinding fineness](image)

### 7. Conclusion

- Four variants of combined schemes for high-ash Ekibastuzsky coal combustion based on a P-57 boiler with various designs of burners and nozzles, their arrangement and distribution of fuel and air between burners and nozzles have been discovered;
- The best fuel burn-up results were achieved in schemes №3 and №4 (\( q_4 = 0.6-0.8\% \) with \( R_{90} = 15\% \) and \( q_4 = 5-5.2\% \) with \( R_{90} = 50\% \)), the worst in scheme №1 (\( q_4 = 1.5-3.3\% \) with \( R_{90} = 15\% \) and \( q_4 > 7\% \) with \( R_{90} = 50\% \));
- The optimal scheme in terms of burnup efficiency and NO\(_x\) formation is scheme № 4 (with the project grinding fineness \( q_4 = 0.8\% \), C\(_{\text{NOx}}\) = 620 mg/m\(^3\));
- The minimum emissions of nitrogen oxides are achieved in the combined scheme №1 with a tertiary air fraction \( \alpha_{\text{ter}} = 0.521 \) C\(_{\text{NOx}}\) = 278 mg/m\(^3\) at \( \alpha = 1.4 \), which meets the regulatory requirements. The maximum emissions correspond to scheme №3 - C\(_{\text{NOx}}\) = 733 mg/m\(^3\) for \( \alpha = 1.4 \);
- Regression analysis showed that the most significant factors affecting the losses \( q_4 \) are the total residue on the sieve \( R_{90} \) and the local excess of air in the zone of active combustion \( \alpha_{\text{ZAC}} \). Least significant factors are the primary air velocity \( \omega_1 \) and the height of the complete combustion zone \( h_{\text{CCZ}} \).

### Acknowledgement

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