Investigation of the direct-flow burners and nozzles arrangement at the direct-flow-vortex coal combustion in a furnace with solid slag removal

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Abstract. The paper presents results of the furnace aerodynamics investigation using direct-flow burners and air nozzles (DFBAN) with solid slag removal (SSR). The studies were performed using the computational fluid dynamics software ANSYS Fluent. The paper includes recommendations for the development of effective solid fuel combustion schemes with DFBAN, methods for researching and optimization of the combustion aerodynamics with the use of DFBAN, optimization criteria, initial data for the study. The scheme for burning Kuznetsk lean coal with the use of DFBAN and SSR was developed. Several series of calculations were performed for the developed scheme. In these calculations, the dependencies of the indicators of efficiency, furnace ecological safety and reliability on the nozzles and burners positions, which are located in the first zone of the scheme, were found. The first stage of the optimization of the developed scheme burning solid fuel with the SSR was made.

1. Introduction

Coal-fired generation occupies a significant part in the power generation structure in the Russian Federation. In 2016, the solid fuel thermal power plants percentage was 34.5 % in the installed capacity of the Russian thermal power plants [3]. Coal occupies a significant part in the organic fuel reserves structure. So coal generation will be significant for a long time for the Russian Federation.

Coal-fired thermal power plants account for the vast gross emissions of pollutants [3]. One of the main pollutants formed during the coal combustion is the nitrogen oxide $NO_x$. Currently, for the low-volatile solid fuel combustion, mainly furnaces with liquid slag removal are used. The feature of this furnace type is the high temperature in the flame core, which contributes to the stable torch burning and maintaining specific unburned carbon loss $q_4$ within acceptable limits. The high temperature in the combustion zone leads to the intensive formation of nitrogen oxides $NO_x$, which emissions exceed the acceptable values in most cases [4]. Vortex burners are mainly used for coal combustion nowadays. Direct-flow burners are not spread because of requiring a detailed study of the furnace aerodynamics. It is mainly used in tangential combustion schemes.

The use of solid fuel combustion schemes with DFBAN can ensure stable ignition and combustion with acceptable values of specific unburned carbon loss $q_4$ and specific emissions nitrogen oxides $NO_x$, that do not exceed the normative [4]. This is evidenced by the Department of thermal Power Plants of the National Research University "MPEI" experience [5]. Modern research methods, such as numerical simulation using computational fluid dynamics (CFD) software, allows to develop the
combustion aerodynamics with sufficient accuracy [1]. These investigations make it possible to create effective solid fuel combustion schemes with DFBAN and to optimize it.

The development of the unified burning low-reactive coal using scheme for furnaces with SSR for boilers of various capacities is very relevant today.

2. Recommendations for the combustion scheme with DFBAN implementation

These recommendations are formulated taking into account the accumulated experience of developing such schemes by the Department of Thermal Power Plants (TPP) [5, 6]:

- the use of the minimum possible primary air excess in dust-air jets for their rapid heating;
- creating a large number of vortices in the furnace volume rotating in opposite directions for better mixing of combustion reactants and equalizing the temperature in the furnace volume;
- organization of hot flue gases supply to the root of fuel-air jets for heating and ignition;
- exclusion of zones of increased dynamic pressure of the flame to the furnace walls to prevent slagging and hydrogen sulfide corrosion;
- stage combustion organization to reduce the nitrogen oxides NO\textsubscript{x} formation;
- organization of the main upward flow of flue gases and fuel particles motion in the middle part of the furnace to reduce the probability of furnace walls slagging;
- exclusion of combustion in a dry bottom hopper to prevent its slagging.

3. Strategy of research and optimization of combustion scheme

The authors proposed the following research program:

1. the choice of the study conducting method;
2. formulation of criteria for combustion scheme optimization;
3. the choice of the initial scheme and data according to the developed recommendations;
4. division of the investigated stage combustion scheme into the three zones;
5. step by step study of stage combustion zones and selection of optimal geometric characteristics of the burners and nozzles position:
   5.1. study of the influence of heights and inclination angles (position) of the I zone nozzles and burners to select the optimal values (only burners and nozzles located in the I zone participate in the study to exclude the influence of flows from the zones II and III; air and fuel are not supplied to the burners and nozzles of the zones II and III);
   5.2. study of the influence of the zone II nozzles and burners position to select an optimal values based on the results of the stage 5.1 (air is not supplied to the nozzles of the zone III);
   5.3. study of the influence of the zone III nozzles position to select the optimal values based on the stages 5.1 and 5.2;
6. study of the optimal number of vertical planes for the burners and nozzles arrangement;
7. research of the furnace cross section thermal specific stress $q_f$ influence on the combustion scheme operation;
8. research of the developed scheme implementation for different loads of the boilers;
9. research of burning coals of various characteristics using the developed combustion scheme.

The following are the results of research on stages 1-5.1 inclusive. Work on the remaining stages will be continued.

4. The choice of the study conducting method

The optimal furnace aerodynamics organization during the solid fuel combustion is a very complex task, including many physical and chemical processes requiring detailed study. The use of CFD for the investigation has sufficient accuracy and was sufficiently mastered by the authors [1]. Therefore, within the framework of this study, the CFD software ANSYS Fluent was used.

For the study, the similar approach to [1] was used. The main features of the model are:
• a geometric furnace 3D model was created in the SolidWorks. Modeling of the flows input into the model was carried out by setting parameters on the plane of their entry into the furnace. Therefore, planes are placed in the places where the streams are entered;
• the mesh is made in the ANSYS ICEM. The main mesh element is tetrahedra with a prismatic layer for more accurate modeling of near-wall layer. The mesh is adapted at the DFBAN area. The adaptation consists in its local size reduction to increase the calculation accuracy. A preview study was performed on the insensitivity of the simulation results to the mesh size;
• combustion simulation in the furnace was carried out in ANSYS Fluent. The selected computational models are shown in Table 1 based on the recommendations [7-10]. The type of boundary conditions is presented in Table 2. For the feature of fuel grinding the Rosin-Rammler equation [11] was used. Iterative modeling was carried out until the values of the residuals were reached $10^{-3}$ (the energy and fraction residuals of the mixture components were up to $10^{-6}$), the mass and energy balance was achieved, as well as the constant values of the control values were established.

| Model                                      |
|--------------------------------------------|
| Turbulence       | k-ε        |
| Radiation        | P-1        |
| Convection and thermal conductivity        | Energy balance |
| Discrete phase   | Discrete Phase Model |
| Volatiles        | Single Kinetic Rate |
| Homogeneous combustion | Species Transport |
| Solid fuel combustion | Kinetics/Diffusion Limited Rate |
| Slagging         | User Defined Function |
| NO$_x$ formation | Thermal/fuel/prompt formation models |

| Boundary condition             | Type          |
|--------------------------------|---------------|
| Air inlet to the model         | inlet         |
| Combustion products outlet from the model | pressure-outlet |
| Water walls                    | wall          |

### 5. Combustion scheme optimization criteria

The scheme should ensure an environmental safety, economical and reliable operation of the boiler. Therefore, the optimization criteria should characterize the furnace operation in these areas.

The reliability indicators of the boiler are: the average operating time for failure, the coefficient of technical use, the availability factor, the estimated service life, the lifetime maintenance between major repairs [4]. In this case, the optimization criteria is stable flame combustion, exclusion of intensive slagging of water walls, exclusion of torch burning near waterwalls proximity, ensuring the outlet flue gas temperature of the furnace below the values given in [12].

From the point of view of ensuring the environmental safety the minimization of nitrogen oxides NO$_x$ mass concentrations in flue gases at an excess air ratio $\alpha$, ($C_{NOx}$, mg/nm$^3$) was chosen as an optimization criterion [4]. Their values should not exceed the standard values.

According to [4, 13] the gross efficiency is used as an economical operation indicator of the boiler unit, therefore the unburned carbon losses ($q_4$, %) minimization is chosen as the optimization criterion.
6. Initial scheme and data selection for the research
The initial scheme for the research was based on the experience of the TPP Department NRU "MPEI", which provides the usage of DFBAN [2, 14]. Taking into account the positive features of the schemes [2, 14], as well as the above recommendations, the authors developed the scheme for the research (figure 1). The scheme is designed for a double-shell boiler of 1030 t/h steam capacity with reheater, working on lean Kuznetsk coal with a holding dust bin. The characteristics of the investigated boiler and fuel [12] are given in Tables 3 and 4, respectively.

Table 3. The characteristics of the investigated boiler.

| Units           | Value |
|-----------------|-------|
| Steam capacity  | t/h   |
| Reheated steam capacity | t/h |
| Steam temperature | °C   |
| Steam pressure  | MPa   |
| Reheated steam temperature: | |
| - inlet         | °C   |
| - outlet        | °C   |
| Reheated steam pressure: | |
| - inlet         | MPa  |
| - outlet        | MPa  |
| Feed water temperature | °C |

Table 4. Fuel characteristics (as received).

| Moisture | Ash content | N | S | O | H | C | V\text{daf} | LCV |
|----------|-------------|---|---|---|---|---|-------------|-----|
| Units    | %           | % | % | % | % | % | %          | %   |
| Value    | 10.0        | 16.2|1.7| 0.3| 3.0| 65.7|13.0        | 24.7|

To organize three-stage combustion, the scheme was divided into three zones in height. So 80% of the fuel is supplied to the zone I with a local excess air ratio $\alpha_{\text{locI}} = 1$, the rest fuel (20%) is supplied to the zone II with a local coefficient of excess air $\alpha_{\text{locII}} = 0.9$, the remaining air is supplied to the zone III $\alpha_{\text{locIII}} = \alpha_{\text{furnace}} = 1.15$. Table 5 shows the excess air coefficients through the nozzles and burners $\alpha_i$, as well as the flow rate of jets from them in accordance with the recommendations [16, 17].

Table 5. Velocities and excess air ratios in nozzles and burners.

| Units | B1  | B2  | SA  | DB  | TA2 | TA3 |
|-------|-----|-----|-----|-----|-----|-----|
| Excess air ratio, $\alpha_i$ | -  | 0.070| 0.020| 0.442| 0.268| 0.080| 0.250|
| Velocity, $w_i$ | m/s | 25  | 25  | 45  | 20  | 45  | 45  |

In this scheme, the nozzles of the SA are located opposite each other horizontally to prevent the coal-dust particles falling into the dry bottom hopper, as well as to cool it, which contributes to the normal operation of the SSR. There is a vortex, which is formed by flows from DB, B1 and SA, in the middle part of the zone I. The vortex promotes intensive combustion components mixing, as well as hot combustion products recirculation to the root of the fuel-air jet, contributing to its ignition. The fuel-air jet from B2 and tertiary air from TA2 enters the zone II, and tertiary air from TA3 enters the zone III.
Burners and nozzles are located in six vertical cross sections of the furnace (1-1, 2-2, 3-3, 4-4, 5-5, 6-6). In this case, in adjacent cross sections, the position of the nozzles and burners is mirrored relative to the axis of furnace symmetry. Thus, there are vortices rotating in different directions in adjacent vertical cross sections. This contributes to the flow turbulization, better mixing of the combustion components, and stable combustion.

For the selected characteristics of the boiler and fuel the thermal calculation of the boiler and the dust preparation system was carried out, according to the methods [12] and [15], the main results of which are summarized in Tables 6 and 7.

Table 6. Boiler and furnace thermal calculations results.

| Units                        | Value |
|------------------------------|-------|
| Hot air temperature          | °C 300|
| Flue gas temperature         | °C 135|
| Boiler efficiency            | % 89,92|
| Fuel consumption             | t/h 64,138|
| Width of the furnace         | m 17,0 |
| Depth of the furnace         | m 10,5 |
| Cross-sectional area of the furnace | m² 178,5 |
| Furnace cross-sectional heat release rate | watt/ m² 2,37 |
| Air excess ratio at the exit of the furnace | - 1,15 |
| Leaked-in air ratio          | - 0,02 |
Table 7. Dust preparation system thermal calculations results.

| Units                | Value                                                                 |
|----------------------|----------------------------------------------------------------------|
| Mill type            | ball-mill pulverizer 370/850 (50A)                                    |
| Number of mills per body | 1                                                                       |
| Dust moisture behind the mill | % 2,0                                                                  |
| Drying agent temperature behind the mill | °C 120                                                               |
| Excess air ratio in dump burners | - 0,268                                                            |
| Burner inlet air temperature | °C 226                                                                |
| Excess air ratio in burners | - 0,1                                                                    |
| Pulverized coal cyclone efficiency | % 90                                                                  |

7. Initial scheme and data selection for the research

Figure 2 shows an initial scheme geometric 3D model and its mesh. The height of the model is 30 m.

As a simulation result $q_4 = 8,27 \%$, $C_{NOx} = 360 \text{ mg/nm}^3$, with a standard value of $C_{NOx} = 350 \text{ mg/nm}^3$ [4], the flue gas temperature at the output of the model is $t_m = 1064 \degree \text{C}$, temperature distribution fields, current lines, vector fields were obtained (Figure 3).

Figure 3a shows that a zone with a high temperature is observed in the pulverized coal jet input area of B1, which indicates its reliable ignition. In addition, a high temperature zone is observed above and below B1 from the high-temperature combustion products recirculation to the B1 root (Figure 3b), which also contributes to its reliable ignition. The figure 3e shows a set of vortices in the furnace central part, formed by the opposite movement of the jets located in adjacent vertical sections, which contributes to the intensive combustion components mixing. Figure 3b shows that the main part of the gaseous phase moves in the furnace central part, but Figure 3d shows that a significant part of the pulverized coal particles hits waterwalls and does not participate in the reaction process, therefore the probability of waterwalls slagging increases.

To improve the economic and ecological indicators, as well as the furnace reliability with the developed nozzles and burner layout, their location was optimized. The results of optimization are carried out further.
Figure 3. Visualization of initial scheme simulation results: (a) – the temperature field at the section 4-4 (Fig. 1); (b) – the streamlines of the DFBAN located at the section 4-4 (Fig. 1); (c) – the velocity vector field at the section 4-4 (Fig. 1); (d) – the coal particles trajectory of the B1 and the DB located at the section 4-4 (Fig. 1); (e) – the velocity vector field in the horizontal section at the level of B1.

8. Research and optimization of zone I

The optimization of the initial scheme was made step-by-step starting with zone I. To exclude the influence of the DFBAN of the zones II and III, their boundary condition was changed to wall. An important task was to organize the main upward of the dust-air flow closer to the furnace centre. The general scheme for the optimization is shown at Figure 4. It is important that this scheme is a dimensionless, which makes it possible to implement it for boilers of various capacities. The SA in this scheme should be placed in height closest to the beginning of the dry bottom hopper inclination.

Optimization was made step by step changing of the angle $\beta_{b1}$, the relative expected contact depth of the B1 and SA jets $b_{b1} = b_{b1}/b_f$ ($b_{b1}$ – the absolute expected contact distance of the B1 jet and SA jet, $b_f$ – furnace depth), the angle $\beta_{db}$, the relative expected contact depth of the DB and B1 jet $b_{db} = b_{db}/b_f$ ($b_{db}$ – the absolute expected contact distance of the DB and B1 jets), the excess air ratio redistribution between SA and B1 (the excess air ratio of the zone I remains constant), the angle $\beta_{es}$.
At the first stage of optimization, an influence of the $\beta_{b1}$, $\beta_{db}$ on the selected optimization indicators made. For this research the DB flow influence is excluded by directing it to the B1 root at the angle $\beta_{db} = 40^\circ$, the SA are directed horizontally $\beta_{sa} = 0^\circ$. The results are summarized in Table 8.

| $b_{b1}$ | $q_4$, % | $C_{NOx}$, mg/nm$^3$ | $t_{m"}$, °C |
|----------|----------|----------------|----------------|
| $\beta_{db} = 4/8$ | 5/8 | 6/8 | 4/8 | 5/8 | 6/8 | 4/8 | 5/8 | 6/8 |
| $\beta_{db} = 30^\circ$ | 9,30 | 6,61 | 8,72 | 434 | 359 | 347 | 971 | 996 | 995 |
| $\beta_{db} = 40^\circ$ | 9,19 | 7,28 | 9,16 | 362 | 291 | 306 | 975 | 1020 | 1012 |
| $\beta_{db} = 50^\circ$ | 9,00 | 8,38 | 9,19 | 389 | 382 | 446 | 1017 | 1028 | 1030 |
| $\beta_{db} = 60^\circ$ | 8,73 | 8,43 | 11,50 | 401 | 412 | 426 | 1011 | 1038 | 1102 |

The lowest value of $q_4$ is observed at $\overline{b_{b1}} = 5/8$. It is explained by the fact that at $\overline{b_{b1}} = 4/8$, a part of coal particles penetrates the dry bottom hopper. At $\overline{b_{b1}} = 6/8$ some particles are pushed up to the opposite wall and thus in both cases does not participate in combustion. At $\overline{b_{b1}} = 5/8$, there is no throwing of particles on the opposite wall, as well as its penetration into the dry bottom hopper.

With an increase of $\beta_{b1}$ at $\overline{b_{db}} = 5/8$ and $\overline{b_{b1}} = 6/8$, the $q_4$ grows since the installation height of B1 increases, therefore, the fuel-air jet is less mixed with the air flow. In the case of $\overline{b_{b1}} = 4/8$ $q_4$ decreases with an increase of $\beta_{b1}$ because of less part of the coal particles enters the dry bottom hopper and most part of it will be burnt in the furnace with increasing of B1 installation height.

Analyzing Table 8 for further optimization $\overline{b_{b1}} = 5/8$ was selected at $\beta_{b1} = 30^\circ$, since it has the best indicator $q_4 = 6,61$ % and the lowest flue gas model outlet temperature $t_{m"} = 996$ °C. The value of $C_{NOx} = 359$ mg/nm$^3$ slightly exceeds the standard value and can be improved with further optimization. At the same time, a maximum temperature is observed at the wall opposite to the wall of the B1 installation, what increases the probability of its slagging, what requires adjustments in the optimization process. The research of the angle below $\beta_{b1} = 30^\circ$ was not carried out, since this will lead to the movement of the maximum temperature position even closer to the waterwalls.

The similar research was made for the DB. To select the optimal $\overline{b_{db}}$ the study was carried out at the constant angle $\alpha_{db} = 40^\circ$. The results are presented in Table 9. Decreasing of $\overline{b_{db}}$ leads to the increasing of temperature in the area of bottom hopper, what is negative for the SSR. For further studies the $\overline{b_{db}} = 8/8$ was chosen, since it has the best economic indicators. Values of $\overline{b_{db}}$ lower than $5/8$ were not considered, since it will lead to a violation of the combustion products circulation to the B1, which will worsen the fuel-air jet heating and ignition process.
Table 9. The $\overline{b_{db}}$ influence on the furnace operation.

| Units | Value |
|-------|-------|
| $b_{db}$ | 8/8 7/8 6/8 5/8 |
| $q_4$ | % 6.61 8.63 7.26 6.67 |
| $C_{NOx}$ | mg/nm$^3$ 359 310 273 169 |
| $t_m$ | $^\circ$C 996 1011 1022 1031 |

In case $\overline{b_{db}} = 8/8$ the $b_{db}$ influence on furnace operation was made (Table 10). The optimal case has $b_{db} = -10$ $^\circ$ (DB is directed upwards), since the lowest values of $q_4 = 5.66\%$ and $C_{NOx} = 129$ mg/nm$^3$. At the same time there is a slight increase in the flue gas temperature at the model outlet to $t_m = 1076$ $^\circ$C, associated with a change in the position of the flame core along the furnace height. The flame core in this case is located in the furnace center.

Table 10. The $b_{db}$ influence on the furnace operation.

| Units | Value |
|-------|-------|
| $b_{db}$ | $^\circ$ -10 0 10 20 30 40 50 60 |
| $q_4$ | % 5.66 5.51 5.95 6.19 7.09 6.61 9.96 11.58 |
| $C_{NOx}$ | mg/nm$^3$ 129 200 192 276 253 359 360 419 |
| $t_m$ | $^\circ$C 1076 1058 1038 1025 1015 996 1012 1027 |

Next, the excess air ratio redistribution between B1 and SA was researched (Table 11). The values of the $t_m$ and $q_4$ remain almost unchanged, but the $C_{NOx}$ increases slightly with an increase in excess air ratio in the B1 jet. Therefore, the optimal option is chosen with $\alpha_{b1} = 0.07$ (the initial one).

Table 11. Influence of the secondary air nozzles SA installation angle on the furnace operation.

| Units | Value |
|-------|-------|
| $\alpha_{b1}$ | $^\circ$ 0.07 0.12 0.17 |
| $\alpha_{sa}$ | $^\circ$ 0.442 0.392 0.342 |
| $q_4$ | % 5.66 5.47 5.65 6.76 |
| $C_{NOx}$ | mg/nm$^3$ 129 163 188 242 |
| $t_m$ | $^\circ$C 1076 1063 1059 1123 |

Finally, influence of the $b_{sa}$ on the furnace operation was studied (Table 12). The optimal option was chosen at $b_{sa} = -20$ $^\circ$ (with an upward slope), since it has good indicators ($C_{NOx} = 179$ mg/nm$^3$ and $q_4 = 5.65\%$), and has more suitable temperatures at the dry bottom hopper for the SSR.

Table 12. Influence of the secondary air nozzles SA installation angle on the furnace operation.

| Units | Value |
|-------|-------|
| $b_{sa}$ | $^\circ$ 0 -10 20 30 |
| $q_4$ | % 5.66 5.39 5.65 6.76 |
| $C_{NOx}$ | mg/nm$^3$ 129 151 179 242 |
| $t_m$ | $^\circ$C 1076 1084 1108 1123 |

Figure 5 shows DFBAN optimized layout of the I zone and a visualization of its modeling results. Table 13 summarizes the values of the geometric burner and nozzles position characteristics of the developed scheme I zone of the developed scheme, obtained during the step-by-step optimization.
Table 13. Optimal values of DFBAN arrangement.

| $\beta_{b1}$ | $\beta_{sa}$ | $\beta_{db}$ | $\beta_{b1}$ | $\beta_{bd}$ |
|--------------|--------------|--------------|--------------|--------------|
| $30^\circ$   | $-20^\circ$  | $-10^\circ$  | $5/8$        | $8/8$        |

Figure 5. Simulation results visualization of the proposed scheme after I zone optimization: (a) - the burners and nozzles arrangement; (b) - the temperature field at the vertical section 4-4 (Fig. 1); (c) - the streamlines of DFBAN located at section 4-4 (Fig. 1); (d) - the velocity vector field at section 4-4 (Fig. 1); (e) - the coal particles trajectory of the B1 and the DB located at section 4-4 (Fig. 1).

9. Conclusions

The recommendations developed by the authors for the solid fuel combustion schemes using DFBAN in furnaces with SSR are presented. The methodology of the research and optimizing combustion schemes, optimization criteria characterizing the reliability, efficiency and ecological safety of the furnace (the absence of slagging, minimum unburned carbon loss $q_{u}$, minimum values of nitrogen oxides in flue gases $C_{NOx}$ mass concentrations with an excess air ratio $\alpha = 1.4$) are presented.
As an initial scheme for research and optimization, a combustion scheme with a holding bin has been developed corresponding to the formulated recommendations. The initial data for optimization was made. Numerical simulation of the initial scheme was carried out.

An approach to step-by-step aerodynamics optimization of three-stage combustion zones is proposed, which excludes the burners and nozzles influence of above-located zones.

The zone I optimization of the developed scheme was carried out using numerical simulation. The optimal values of the installation angles and the position of the secondary air nozzles $SA (\beta_{sa}=-20^\circ)$, the dump burners $DB (\beta_{db}=-10^\circ, \beta_{db1} = 8/8)$, the zone I burner $B1 (\beta_{b1}=30^\circ, \beta_{b1} =5/8)$ were determined. The obtained characteristics are presented in a dimensionless form, which makes it possible to apply the optimization results for boilers of different capacities.

The developed scheme optimization will be continued in accordance with presented strategy.

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