Investigation of the interaction of turbulent jets in furnaces with direct-flow burners for high-power boilers

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Abstract. The aim of the study is to develop a highly efficient scheme of combustion of low-grade solid fuels with the realization of regulatory requirements for emissions of hazardous substances into the atmosphere. One of the directions of practical application of such a scheme is conversion of boilers with liquid slag removal to solid slag removal. Liquid slag removal boilers have a number of disadvantages that make their use in modern conditions impractical: reducing the reliability of the liquid slag at low loads and high emissions of NOx nitrogen oxides, which exceed the standard values 2-3 times. In light of amendments to the environmental legislation of the Russian Federation, changing the order and rates of payment for emissions of hazardous substances from 2020, thermal power plants will be forced to implement environmental measures to ensure normative values of specific emissions. The basic principles of effective solid fuel burning organization with the application of direct-flow burners have been formulated on the basis of the conducted research.

1. Introduction
In light of amendments to the environmental legislation of the Russian Federation, changing the order and rates of payment for emissions of hazardous substances from 2020 [1,2] thermal power plants (TPP) will be forced to implement environmental measures to ensure normative values of specific emissions. For this purpose a scheme of solid fuel combustion in a direct-flow vortex flame (DFVF) was developed, Fig. 1, on the basis of former developments of Moscow Power Engineering Institute (MPEI) [3]. This scheme was designed for furnaces of powerful boilers with medium heat release rate and dry slag removal, corresponding to the main current trends in the development of solid fuel boiler technology [4]. Bituminous coal with the following main thermal characteristics was selected: \( Q^f_1 = 25750 \text{ kJ/kg} \), \( V^\text{daf} = 16.6 \% \), \( C^r = 68.62 \% \), \( H^r = 3.35 \% \), \( N^r = 1.75 \% \), \( S^r = 0.23 \% \), \( O^r = 2.13 \% \), \( A^r = 16.92 \% \), \( W^r = 7.0 \% \). It should be noted that the emissions of sulfur oxides do not depend on the fuel combustion mode, and will be the same as on similar boilers with any burner devices with this type of fuel.

The purpose of the arrangement of burners and nozzles shown in Fig. 1 is the provision of staged combustion of coal dust, obtained in jar roller mills. Coal dust after grinding is fed into the pulverized-coal burners (PCB), and the channels of gas-oil burners (GOB) are used when working on reserve fuel: oil or gas. When working on solid fuel, air is supplied to the GOB. The GOB is adjacent to the PCB without rupture. A distinctive feature of this scheme is the stabilization of the resulting direct-flow-vortex flame (DFVF) with the help of the lower blast, carried out through the secondary burnout air nozzles (SBAN). Tertiary burnout air nozzles (TBAN) are installed in front of the corresponding...
PCB/GOB, and have rectangular cross sections. The angles of the PCB/GOB installation are selected from the condition of the most complete filling of the formed 4 vertical oppositely rotating relative vortices (in terms of the number of PCB) in the volume of the furnace bottom. Counter-displaced arrangement of burners and nozzles allows organizing three zones of mass transfer in the horizontal plane with the opposite movement of masses relative to neighboring zones in the volume of the model. Estimated values of the air excess for the boiler were as follows: $\alpha_{PCB} = 0.288$, $\alpha_{GOB} = 0.325$, $\alpha_{SOAN} = 0.0813$, $\alpha_{TOAN} = 0.436$, and furnace air inflow $\Delta \alpha_F = 0.02$.

Figure 1. Arrangement of direct-flow burners and nozzles in the implementation of solid fuel combustion:
- PCB – pulverized-coal burners;
- GOB – gas-oil burners;
- SBAN – secondary burnout air nozzles;
- TBAN – tertiary burnout air nozzles.

The aim of the research is to develop and generalize the principles of optimization of the aerodynamics of the furnace volume of steam boilers, to study new solutions and schemes for the organization of DFVF (with a staged supply of an oxidizer to fuel) to reduce nitrogen oxide emissions, to improve reliability and expand the range of steam loads.

The main feature of the developed scheme is the use of direct-flow burners and nozzles and the organization of effective staged combustion along the furnace flame. The technology of staged coal combustion provides:
- usage of direct-flow burners, as well as secondary and tertiary air nozzles installed on the counter-offset scheme and directed with a significant downward slope;
- release of fuel jets flowing from the burners from the ballast air masses, which are sent to the SOAN and TOAN;
- installation of SOAN below the level of coal burners and use of these nozzles as GOB for boiler start up or gas combustion;
- forced supply of flue gases to the roots of dusty jets;
- increase in the perimeter of the direct contact of the fuel-air jets with flue gases (ignition perimeter) due to the burners in the form of vertically elongated rectangular channels, significantly tilted downwards, while, as calculations have shown, the small content of volatile in the coal is compensated by an increase in the perimeter of the ignition.

The main advantages of the developed scheme are: the organization of high-efficiency combustion of coal dust; the ease of manufacture and installation of furnace-burner devices; and an increased efficiency of the boiler due to reducing the value of unburned char particles.

2. The main results of the study of aerodynamics of the furnace on the physical model
From the analysis of the similarity criteria, the equations for calculating the main parameters of the isothermal physical model of the furnace with this scheme of burners’ arrangement were obtained.
Then the physical model was built (see Fig. 2). The cycle of studies of the aerodynamics of the furnace on the physical model includes visual observations of the nature of the flow motion, using spark methods for visualizing the motion of jets, their fixation on a digital camera (see Fig. 3), and a quantitative study of velocity and temperature fields.

![Figure 2. Photo of the physical model of high-capacity boiler furnace.](image)

The trajectory of the PCB’s jet is the most important in terms of slagging and abrasion of the side water walls, dry bottom hopper and the ashpit. Figure 3 shows the visualization of the PCB’s jets for a direct injection furnace for the three main flow regimes in cross section I-I (indicated in Fig. 1): with a basic excess of primary air $\alpha_{PCB} = 0.288$ (which allows achieving a significant reduction in the formation of NO$_x$), with a decreased excess of primary air $\alpha_{PCB} = 0.158$ and with a decreased excess of primary air and closed GOB burner channel.

![Figure 3. Trajectories of PCB’s jet in cross-section I-I:](image)

a) basic excess of primary air; b) decreased excess of primary air; c) decreased excess of primary air and closed GOB burner channel.

For these three variants of the flow regimes, studies were conducted to determine the quantitative characteristics of the jets. Formulas have been obtained for calculating the jet mass gain and the coefficient of ejection capacity in relation to experimental studies on a physical model. The jet mass increases mainly by hot flue gases ejection and by forced delivery of flue gases, depending on the relative position of the burners and nozzles.
In all variants appear a strong deformation of the jets and a deviation of their motion trajectories relative to the axis in all three investigated variants. It is explained by the forced delivery of flue gases due to the vortex aerodynamics in the furnace and the mutual influence of turbulent flows on each other. The mass gain of the jets (see Fig. 4) and the ejection capacity of turbulent jets are much larger than in a submerged planar jet. This is explained by the fact that the mass gain in the fuel jet occurs not only due to the ejection of the jet itself, but also due to the forced delivery of flue gases from other jets and from the furnace volume, i.e. due to the in-furnace recirculation, which is generated due to the tangential orientation of all PCB, GOB, SOAN and TOAN jets.

Based on the analysis of aerodynamics of the furnace with a direct-flow-vortex torch, the following conclusions may be drawn:

1. Experiments have revealed high stability of the position of the opposite directional vortices in both vertical and horizontal planes.
2. The high stability of the position of the vortices suggests an increase in the coal dust residence time in the combustion zone and the possibility of burning it at lower temperatures. In sum, along with converting to dry slag removal, it will significantly reduce the formation of nitrogen oxides.
3. Due to low values of excess air at the PCB’s outlet and the gradual supply of air to the vortex zone through several nozzles, staged combustion of coal dust is realized with an increase in its burnout and with a significant amount of internal combustion gas recirculation.
4. The special aerodynamics of direct-flow-vortex flame allows preventing coal and ash particles insertion on the surface of dry bottom hopper, water walls and ashpit of the boiler due to correct mutual arrangement of SOAN, TOAN and GOB jets. This reduces the probability of slagging and abrasion on these surfaces.
5. Comparison of considered variants has shown that in terms of slagging reduction the most beneficial is the variant with \( \alpha_{\text{PCB}} = 0.288 \) and with fully open GOB channels.
6. Comparison of visualization results for flows obtained on physical model with basic and decreased air excess (Fig. 3, a, b) has shown an insignificant difference between them. This indicates that in a real boiler furnace, operational reductions in primary air excess will not significantly affect the results of its work.
7. The variant with closed GOB channels (Fig. 3, c) is not allowed, because of technical limitation due to insertion of PCB’s jets on the walls of dry bottom hopper followed by slagging and overheating of
the water wall system. The GOB channels supplied only by the air when burning coal dust, create an afflux separating the fuel jet from the walls of the dry bottom hopper. When these channels are closed, it may possibly cause a large proportion of unburned fuel particles to fall through the dry bottom hopper.

8. The extended movement trajectory of the flue gases reduces the probability of thermal nitrogen oxides formation, especially in the conditions of the local presence of underburning products. The arrangement of large-diameter vertical vortices in the lower part of the furnace will provide for efficient use of dry bottom hopper water walls, reduce the temperature of the flue gases and the content of unburnt carbon in fly ash.

3. The main results of the study of the furnace aerodynamics in the mathematical model

The method of mathematical modeling was used to study the flow of jets taking into account the simultaneous heat flow. The adopted mathematical model of the furnace includes the following equations: continuity equation (conservation of mass); energy conservation equation; momentum conservation equation; transport of chemical reagents and reaction products equations (diffusion equations); radiant energy transfer equation; state equations; and equations for the discrete phase. For the research, the program complex ANSYS Fluent being a part of program system of the finite element analysis ANSYS [5] is chosen. This software is well suited for solving such cases.

Summarizing the results of numerical simulation of the developed combustion scheme, the following conclusions may be drawn:

1. The concentration of nitrogen oxides at the rated load is 269 mg/Nm$^3$ (with a 6% excess of O$_2$), which is lower than the standard of 350 mg/Nm$^3$ [1].

2. Analysis of gas temperatures in the near-wall zone has shown that there is no excess of the ash softening temperature, which indicates the reliable operation of the water walls under the conditions of slagging.

3. Visualization of mathematical modeling results (see Fig. 5) has confirmed the findings of the research on the physical model. In all the studied modes, one can observe pronounced vortices in the vertical and horizontal planes. This indicates a high degree of mass transfer between the jets and combustion products as well as the stability of the furnace aerodynamics to changes in mode factors.

4. Comparison of modes with open GOB channels shows that in the case of reducing the primary air excess in the PCB jet, vortices in the vertical plane lose their intensity, but become more distinct in the horizontal plane. Consequently, with a decrease in the proportion of air supplied to the burner the mass transfer moves from the vertical to the horizontal plane.

![Figure 5. Velocity vectors of direct-flow vortex torch scheme (with basic excess of primary air), m/s: a) on the axis of PCB (in section I-I); b) on the axis of PCB (in section II-II); c) in the horizontal section at the level of TOAN; d) in the horizontal section at the level of PCB.](image-url)
Thermal and zone calculations of the boiler furnace were performed to obtain the temperature of the flue gases at the outlet of the furnace and the amount of heat received in the furnace. Comparison of the temperatures of gases at the outlet of each zone obtained by mathematical modeling in ANSYS Fluent and zonal calculations show a good match (max deviation of 30°C). Reduced gas temperatures at the top of the furnace in the developed scheme will improve the operating conditions of the platen and ceiling superheaters under the conditions of slagging.

Conclusion

The basic principles of the organization of effective combustion of solid fuel in the application of direct-flow burners have been formulated.

- Adopting the minimum possible excess air for primary air;
- a delay in mixing the secondary air into the flame and the tertiary air supply at the final stage of combustion to the end of the flame;
- providing for internal recirculation of the hot flue gases to the base of flames of burners and nozzles;
- the presence of a significant downward slope of the pulverized-coal burners;
- increasing the perimeter of the ignition;
- spreading the core of the flame on the width, depth and height of the furnace;
- intensive forced supply of flue gases to the base of burner jets for fast ignition of coal dust;
- organizing large number of vortices rotating in opposite directions in the furnace volume;
- exclusion of areas of increased dynamic pressure of the torch on the water walls.

Implementation of solid slag removal when using direct-flow burners and nozzles with a staged combustion allows increasing the stability of fuel combustion, providing low values of minimum stress, eliminating the possibility of slagging of the boiler, and significantly reducing emissions of nitrogen oxides. Direct-flow burners provide efficient and reliable burning of solid fuel only at organizing effective interaction of burner and air jets in the volume of the boiler furnace.

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