Physical and mathematical modeling of solid fuel combustion in the application of direct-flow burners

V B Prokhorov, V S Kirichkov and S L Chernov

Moscow Power Engineering Institute, National Research University (NRU MPEI), Moscow 111250, Krasnokazarmennaia str., 14, Russia

E-mail: ProkhorovVB@mail.ru

Abstract. The tightening of standards for emissions of harmful substances into the air makes it increasingly important to pay attention to fuel combustion technology. The concentration of nitrogen oxides in flue gases on solid fuel boilers, in most cases, exceeds the standard value. The most significant excess in NOx emissions occurs in boilers wit slag-tap removal. The possibility of influence on the aerodynamics of the furnace when using vortex burners, which are individual action burners, on powerful boilers is severely limited. When direct-flow burners, which are collective action burners, there is a possibility of significant impact on the aerodynamics of the active combustion zone. With a rational arrangement of direct-flow burners and nozzles and the use of step combustion, it is possible to provide a significant reduction in the formation of nitrogen oxides, mechanical underburning of solid fuel particles and to prevent the possibility of slag of the screen system. The main problem of using direct-flow burners is the need to study the aerodynamics of each specific combustion volume of different boilers. On the basis of research on physical and mathematical models developed schemes of solid fuel combustion in steam boilers using direct-flow burners and nozzles in the presence of a large number of horizontal and vertical vortices, which should contribute to the efficient combustion of fuel with low emissions of nitrogen oxides.

1. Introduction
The new environmental legislation of the Russian Federation, adopted in 2014, introduces a sharp increase in fees for exceeding technological standards for emissions of harmful substances into the atmosphere, starting from 2020 [1]. At present, the concentration of nitrogen oxides in flue gases is 1300-1900 mg/m³ [2], which is more than two times higher than the current standard [3], when the boilers operate on Kuznetsk coal of the TR brand with slag-tap removal. The reason for this is the liquid method of slag removal that increases the temperature of gases in the pre-furnace, the insufficient excess air at the outlet of the burners (about 0.7-0.8), the increased content of fuel nitrogen in the specified coal grade (N_r = 1.5-1.7%), the use of counter-directed vortex-type burners. These features of technology, especially the last factor, predetermined its additional shortcomings: reliable output of liquid slag without illumination of a pulverized coal torch by high-reactionary fuel is possible only on the raised loadings of a boiler.

When using vortex burners, which are individual action burners, the possibility of influence on the furnace aerodynamics of powerful boilers is severely limited. When using direct-flow burners, which are collective action burners, there is a possibility of significant impact on the aerodynamics of the active combustion zone. With a rational arrangement of direct-flow burners and nozzles and the use of step combustion, it is possible to provide a significant reduction in the formation of nitrogen oxides,
mechanical underburning of solid fuel particles and to prevent the possibility of slag of the screen system.

In FGBOU VO "NRU "MPEI" there is a successful experience of reconstruction of power and water-heating boilers of small and medium power (steam capacity) with the use of direct-flow burners and nozzles with the organization of combustion of fuels in the direct-flow vortex torch [4]. The transfer of boilers to combustion of fuels in the direct-flow vortex torch in most cases led to an increase in reliability, environmental safety and efficiency of the reconstructed boilers.

The main problem of using direct-flow burners is the need to study the aerodynamics of each specific combustion volume of different energy boilers. To check the efficiency of the developed combustion scheme and its efficiency, studies are carried out on the physical model of the boiler furnace and the mathematical model of the experimental furnace stand for the case of isothermal fluid flow (room air). This allows us to compare the results of studies using two different methods [5]. In the future, for the selected scheme, thermal calculations are carried out on a mathematical model taking into account vortex combustion.

2. Scheme of staged combustion of solid fuel for high-power steam boilers using direct-flow burners

On the basis of generalization and analysis of industrial tests of boilers reconstructed by MPEI developments, a scheme of solid fuel combustion in a direct–flow vortex torch was developed (see Fig. 1). This scheme is standardized for the powerful furnaces of boilers with moderate heat stress and the solid bottom-ash removal that meets the basic modern trends in boiler technology for solid fuels.

![Figure 1](image_url)

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

The main purpose of the layout diagram of the burners and nozzles shown in Fig. 1, – the provision of staged combustion of coal dust received in bowl mills scheme with direct injection. Coal dust after grinding is fed into the PCB channels, GOB channels are used when working on reserve fuel – fuel oil or gas. When working on solid fuel, air is supplied to the GOB. To the pulverized coal burner (PCB) the gas-oil burner (GOB) is added without empty space between them. A distinctive feature of this scheme is the stabilization of the vortices formed by the lower blast carried out through the secondary overfire air nozzle (SOAN). The nozzles of the tertiary overfire air nozzle (TOAN) is installed in front of the relevant PCB (GOB), and have a rectangular cross section. The angles of the PCB/GOB installation are chosen from the condition of the most complete filling of the formed 4 vertical vortices (in terms of the number of PCB), oppositely rotating relative to the neighboring ones, the volume of
3. Aerodynamics study of coal dust staged combustion scheme on a physical model

The task of these studies is to exclude zones of high dynamic pressure of the torch on the heating screen surfaces and to ensure the dispersion of the torch core in the width and height of the furnace with timely supply of secondary and tertiary air in the zone of active combustion of fuel. Efficient step-by-step combustion of fuel will reduce the formation of fuel nitrogen oxides. An elongated path of combustion products reduces the probability of formation of thermal nitrogen oxides, especially in terms of local presence of unburned carbon. The location of large diameter vertical vortices in the lower part of the furnace will effectively use the heating surface of the cold funnel, reduce the temperature of the combustion products and reduce the fuel content in the fly ash.

The greatest interest from the point of view of the probability of slagging and wear of the side walls, the cold of the funnel chest and slag of the boiler causes the trajectory of the jet of PCB. Fig. 2 shows a flow visualization of the jet PCB for heating with direct injection of expenditure for the three main modes in the cross section I-I shown in Fig. 1: with a basic excess of primary air \( \alpha_{PCB} = 0.288 \), allowing to achieve a significant reduction in the formation of NO\(_x\), with a reduced excess of primary air \( \alpha_{PCB} = 0.158 \), with a reduced excess of primary air and a closed channel of the gas-oil burner GOB.

The following conclusions can be drawn based on the results of studying the furnace aerodynamics with implementation direct-flow vortex torch:

1. The purges revealed a sufficiently high stability of the counter-directional vortices in both vertical and horizontal planes. It should be noted for comparison that the zone of collision of counter-directed torches of vortex burners is characterized by much less stability of its position.

2. The high stability of the vortex position suggests an increase in the residence time of coal dust in the combustion zone and the possibility of burning it at lower temperatures, which ultimately, together with the transition to slag-tap removal, will significantly reduce the formation of nitrogen oxides.

3. Due to the low values of excess air at the outlet of the PCB and the gradual supply of air to the vortex zone through several nozzles, a stepwise combustion of coal dust is realized with an increase in the degree of its combustion and the temperature of the gases along the length of each vortex with a significant internal recirculation of the combustion products into the roots of the jets.

4. The organization of the combustion aerodynamics in direct-flow vortex torch allows to prevent the ingress of coal and ash particles on the surface of the cold funnel slopes, walls and in the slag chest due to the correct mutual arrangement of SOAN, TOAN and GOB jets. This reduces the chance of slag and wear on these surfaces.

5. Comparison of variants showed that the most preferable in terms of reducing the probability of slag is a variant of with air \( \alpha_{PCB} = 0.288 \) and with fully open channels of GOB.

6. Comparison of flow visualization results obtained on models with basic and reduced air excess (Fig. 2, a, b), showed their insignificant difference. This indicates that in a real furnace operational reduction of primary air flow will not significantly affect the results of its work, unless there is a significant increase in the humidity of the finished dust and increase underburning.

7. The variant with closed GOB channels (Fig. 2, c) not allowed, because a serious technical limitation is the ingress of PCB jets on the slopes of the cold funnel, followed by slagging and overheating of the screen system. GOB channels, which are just fir conduct when coal dust is burned, create a cushion separating the fuel jet from the cold funnel slopes; when these channels are closed, it is possible that a large portion of unburned fuel particles fall through the cold funnel.
Figure 2. The jets PCB trajectory of the direct-flow vortex torch scheme in cross section I-I Fig. 1:
   a) basic excess of primary air; b) reduced excess of primary air; c) reduced excess of primary air and closed GOB channels.

4. Study of aerodynamics of coal dust staged combustion scheme on a mathematical model

The method of numerical simulation was used for further investigation of the outflow of jets taking into account the simultaneous flow of heat exchange processes, diffusion of substances in the gas stream and chemical reactions in the boiler furnace.

The well-proven ANSYS Fluent complex, which is a part of the universal software system of finite element analysis ANSYS, was chosen as a software environment for research in the work, as it has sufficient functionality that is suitable for the tasks of this work and is successfully used in the problems of modeling combustion in boiler plants [6].

Verification of the numerical model, including: analysis of grid sensitivity and analysis of the influence of the solver on the convergence and results of the solution. The results showed that changes in the parameters of the grid and the solver change the average values of input / output velocities and pressures not more than 1%. Validation of the numerical model was performed, which consisted in comparing the simulation results with the experimental data obtained at the laboratory bench. The comparison of the maximum velocities along the PCB on the cut-off depending on the distance from the lower boundary according to the results of numerical and physical modeling showed an acceptable coincidence.

Visualization of numerical simulation results (see Fig. 3) confirmed the conclusions made on the results of studies of the expiration of jets on the stands. In all studied modes, pronounced vortices are observed both in the vertical and in the horizontal plane, which indicates a high degree of mass transfer between the jets and combustion products and the stability of the furnace aerodynamics to changes in the regime factors.

In the mode with a basic excess of primary air, the burner jets have the highest kinetic energy, in the mode with closed GOB channels the least. The weakening of the burner jets in a mode with closed GOB channels leads to their adherence to the walls of the furnace, which is unacceptable under the terms working without slag creation.
Comparison of regimes with open GOB channels shows that in the case of reducing the excess of primary air in the PCB jet, the vortices in the vertical plane lose their intensity, but the vortices in the horizontal plane become more outlined. Consequently, with a decrease in the proportion of air supplied to the burner, the mass transfer is shifted from the vertical plane to the horizontal.

Figure 3. 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 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.

Conclusion
Aerodynamic features of the torch, developed with the help of research on physical and mathematical models, will provide:
– dispersion of the torch core in width, depth and height of the furnace;
– a high degree of mixing of reagents, which is due to the counter nature of the mutual movement of neighboring jets, as well as combustion products in neighboring vertical vortex formations;
– intensive forced supply of flue gases to the roots of the burner jets, i.e. the implementation of early ignition of coal dust;
– defense side of the furnace screens from the dynamic pressure torch burners of opposing walls through a dynamic exposure to fresh opposite jets of burners and nozzles;
– involvement in the combustion of a significant amount of cold air sucked in the lower part of the furnace into the fresh jets of burners and nozzles due to the turbulence of the flows.

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

References
[1] Federal’nyi zakon №219, 22.07.2014 O vnesenii izmeneniy v Federal’nyi zakon «Ob okhrane okruzhayushchey sredy» i otdel’nye zakonodatel’nye akty RF [On amendments to the Federal law “About environmental protection” and separate legislative acts of the Russian Federation. Law of the Russian Federation no 219]. Moscow.
[2] Arkhipov A.M., Kanunnikov A.A., Kirichkov V.S., Prokhorov V.B., Fomenko M.V., Chernov S.L. 2017 Efficiency of Using Direct-Flow Burners and Nozzles in Implementation of Dry-Bottom Ash Removal at the TPP-210A Boiler Furnace. Therm. Eng. 2 (64) 134–141.
[3] GOST R 50831-1995, 1995 Ustanovki kotel’nye. Teplomekhanicheskie oborudovanie. Obshchie tekhnicheskie trebovaniya [State standard R 50831-95. Boiler plants. Heat-mechanical equipment. General technical requirements]. Moscow.
[4] Arkhipov A.M., Lipov Yu.M., Prokhorov V.B., 2013 *Using Strait-Flow Burners and Nozzels in Burner Furnaces: Moscow Power Engineering Institute’s Innovative Experience* (MPEI Publishers, Moscow) [in Russian].

[5] Prokhorov V.B., Chernov S.L., Kirichkov V.S., Kaverin A.A. 2018 Investigation of a Boiler’s Furnace Aerodynamics with a Vortex Solid Fuel Combustion Scheme on Physical and Mathematical Models. *Problemele Energeticii regionale*. 1 (36) 1–11.

[6] Filkoski Risto V., Petrovski Ilija J., Karas Piotr. 2006 Optimisation of pulverised coal combustion by means of CFD/CTA modelling. *Thermal Science (An International Journal)*. Vol. 10, No. 3 161-170.