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Studying the Aerodynamics of the TPP-210A Boiler Furnace When It Is Shifted to Operate with Dry-Ash Removal and Vortex Fuel Combustion

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Abstract—To reduce the amount of nitrogen oxide emissions and achieve more reliable operation of the TPP-210A boiler, a process arrangement for firing Grade TR Kuznetsk coal that involves using straight-flow burners and shifting the boiler from slag-tap to dry-ash removal is developed. Owing to a large burner downward slope angle and special arrangement of burners and nozzles, four large vertical vortices rotating in opposite directions are produced in the furnace lower part, as a result of which the combustion products dwell for a longer period of time in the burning zone and more complete fuel combustion is achieved. For verifying the operability and efficiency of the proposed combustion arrangement, investigations on a boiler furnace physical model were carried out using a technique for visualizing fuel jets and secondary and tertiary overfire air jets. The fuel jet temperature boundaries in the course of jet propagation in the furnace model are also determined. The study results have shown that staged fuel combustion will be set up with using the proposed arrangement of burners and nozzles. In addition, large vertical vortices produced in the furnace lower part will help to achieve more efficient use of the dry bottom hopper heating surfaces, due to which lower coal combustion product temperature in the furnace upper part and smaller content of combustible products in fly ash will be obtained. Owing to low values of air excess factor at the pulverized coal burner outlet and gradual admission of air into the vortex zone through a few nozzles with intense inner recirculation of combustion products to the jet initial section, staged combustion of pulverized coal and low nitrogen oxide emissions will be secured. Owing to expansion of fuel jets, a rapid growth of mass in the fuel jet is achieved, which is obtained both due to ejection of the jet itself and due to forced admission of hot fuel gases from other jets. Investigations carried out on the physical model have confirmed that the proposed combustion arrangement features high efficiency and that a low content of nitrogen oxides in flue gases is obtained.

Keywords: boilers, dry-ash removal, straight-flow burners and nozzles, physical model, nitrogen oxides

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Beginning in 2020, the new environmental legislation of the Russian Federation [1] will stimulate a much higher payment for exceeding the technological norms established for emissions of harmful substances into the atmosphere. At present, the concentration of nitrogen oxides in the flue gases from operating slag-tap boilers usually reaches 1300–2000 mg/m^3, which is a factor of 2–4 higher than the technological norm equal to 700 and 570 mg/m^3, respectively, for boilers commissioned before and after 2001 [2]. Such high concentrations of NO_x result from a high temperature of gases in the fuel combustion zone along with very limited possibilities for implementing methods aimed at suppressing the generation of nitrogen oxides in slag-tap furnaces. Slag-tap boilers are used in Russia in firing anthracites, semianthracites, lean coals, and, in some cases, also brown coals.

Wider opportunities for applying methods for suppressing the generation of nitrogen oxides become available in shifting boilers to operate with dry-ash removal. This circumstance, taken together with a lower temperature of gases in the combustion zone of furnaces in such boilers are factors that open the possibility to achieve essentially lower NO_x emissions as compared with slag-tap boilers and to pay several times smaller sums of money for pollution of the environment. In addition, dry-ash boilers can operate in a wider load adjustment range as compared with slag-tap boilers.

Specialists of National Research University Moscow Power Engineering Institute (NRU MPEI) have gained extensive experience with low-cost modification of boilers aimed at shifting them from slag-tap to dry-ash removal with the use of straight-flow burners and nozzles [3]. According to this experience, the following conditions must be met to secure efficient and reliable fuel combustion with dry ash removal and low nitrogen oxide emissions:

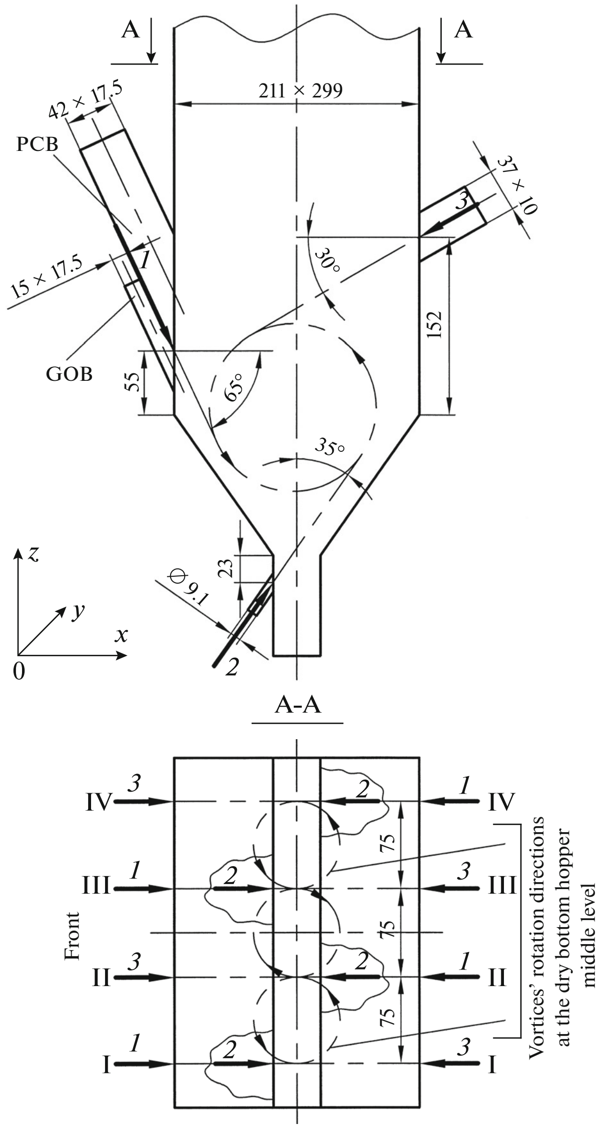

Fig. 1. Sketch of the isothermal physical model. *1*—PCB/GOB; *2*—SOAN; and *3*—TOAN. The layout in the vertical planes passing through neighboring PCB/GOB is according to a mirror image.

1. To secure quick heating and early ignition of fuel, minimal primary air excess factors in pulverized coal—air jets should be adopted. Measures should also be taken for the secondary overfire air to be admixed to the flame with a delay, and for the tertiary overfire air to be admitted to the flame tail part at the combustion final state. The furnace aerodynamics should be arranged so as to ensure internal recirculation of hot furnace gases into the initial part of burner and nozzle jets.

2. For the fuel to dwell in the furnace chamber for a longer period of time and to obtain a larger ignition perimeter, the burners should be oriented at a significant slope downwards. To obtain a larger ignition perimeter, burners with a vertically stretched rectangular shape can also be used. The taking of these measures helps to decrease underburning and to obtain early ignition of fuel and its reliable combustion.

3. For the flame to be uniformly distributed over the furnace width, depth, and height, it is necessary to produce a large number of oppositely rotating vortices in the furnace volume, due to which a more uniformly distributed temperature in the furnace volume, a lower maximum temperature, and better agitation of combustion products will be obtained.

4. Measures should be taken to prevent the occurrence of zones with an increased dynamic pressure of flame containing reducing medium exerted on the waterwall tubes. This will make it possible to decrease the temperature level at the waterwall tubes and to prevent the occurrence of hydrogen sulfide corrosion and waterwall fouling with slag.

In this article, we present the results from studying the aerodynamics of the TPP-210A boiler furnace on its physical model when having been shifted from slag tap to dry-ash removal according to a new technology of staged combustion in a system of neighboring vertical oppositely rotating vortices with direct injection of TR Kuznetsk coal pulverized by means of ball mills. The study results for the TPP-210A boiler modification version involving its shifting for dry ash removal and using the coal pulverization system with an intermediate dust bunker (known as an indirect-fired system) are reported in [4].

The investigations were carried out on a boiler furnace physical model (Fig. 1), the dimensions of which, as well as the parameters of medium at the outlets from the burners and nozzles were selected subject to fulfilling the similarity criteria [3]. The main purpose of the schematic layout of burners and nozzles depicted in Fig. 1 is to set up staged combustion of directly injected pulverized coal obtained from bowl mills. Only half of the TPP-210A boiler was modeled; its second half was identical with the first one. The jets going out from the burners and nozzles were visualized in the course of investigations by means of spark blowing, and the pulverized coal jet's key motion parameters were estimated based on determining its thermal boundaries.

The pulverized-coal and gas/oil burners (PCBs and GOBs) are arranged on the model's frontal wall in vertical sectional views I—I and III—III, and the tertiary overfire air nozzles (TOANs) are arranged on the rear wall. The same sectional views show the secondary overfire air nozzles (SOANs), which are arranged in the ash pit left wall's upper part. The burners and nozzles shown in vertical sectional views II—II and IV—IV are arranged according to a mirror image. For studying the furnace operation mode with a smaller fraction of air supplied to the model through the PCBs, restriction orifices with a flow pass section of 31 × 13 mm were installed upstream of these burners. Furnace operation modes without installing restric-

Fig. 2. Jet motion trajectories from the (a) TOAN, (b) PCB, (c) GOB, and (d) SOAN in section II–II.

tion orifices upstream of the PCBs and with closing the GOB channels (with restriction orifices installed upstream of the PCBs) were also investigated. The burner and nozzle setting angles were selected proceeding from the condition of maximally filling the furnace lower part volume with the four produced vortices (according to the number of PCBs) rotating in the opposite directions with respect to the neighboring vortex formations.

Spark blowing operations were carried out on the model in accordance with the procedure described in [3]; the aim of such operations was to obtain a general motion pattern of all jets in the model volume, including those from the pulverized coal burner, gas/oil burner, and secondary and tertiary overfire air nozzles. The flows were visualized sequentially for each flow and individually for each section with setting up the appropriate velocities in all channels throughout the entire experiment.

As an example, Fig. 2 shows the results of spark blowing operations on the model in section II–II.

The pulverized-coal burner jet evolvement trajectory is of most interest from the viewpoint of fouling and wear probability of the boiler lateral walls, dry bottom, and ash pit. As an example, Fig. 3 shows visualization of the PCB jet flows in section II–II for three main operating modes in terms of flow conditions: with the primary air excess factor $\alpha_{PCB} = 0.288$, at which it is possible to obtain a significantly smaller amount of NO_x generation [version (a)]; with a decreased primary air excess factor $\alpha_{PCB} = 0.158$ [version (b)]); and with a decreased primary air excess factor and closed gas/oil burner channel [version (c)]). As is seen from Fig. 3, variation of the air fraction supplied to the model through the pulverized coal burner does not have a noticeable effect on the visible jet outflow patterns from the PCB.

An analysis of the results from qualitatively studying the aerodynamic features of the proposed combustion arrangement allows us to draw the following conclusions:

1. The oppositely directed vortices in both the vertical and horizontal planes feature quite stable locations. This will help increase the pulverized coal dwelling time in the combustion zone and obtain more complete combustion of fuel.

2. Owing to low values of air excess factor at the PCB outlets and gradual supply of air to the vortex zone through a few nozzles and intense internal recirculation of combustion products to the jet initial part,

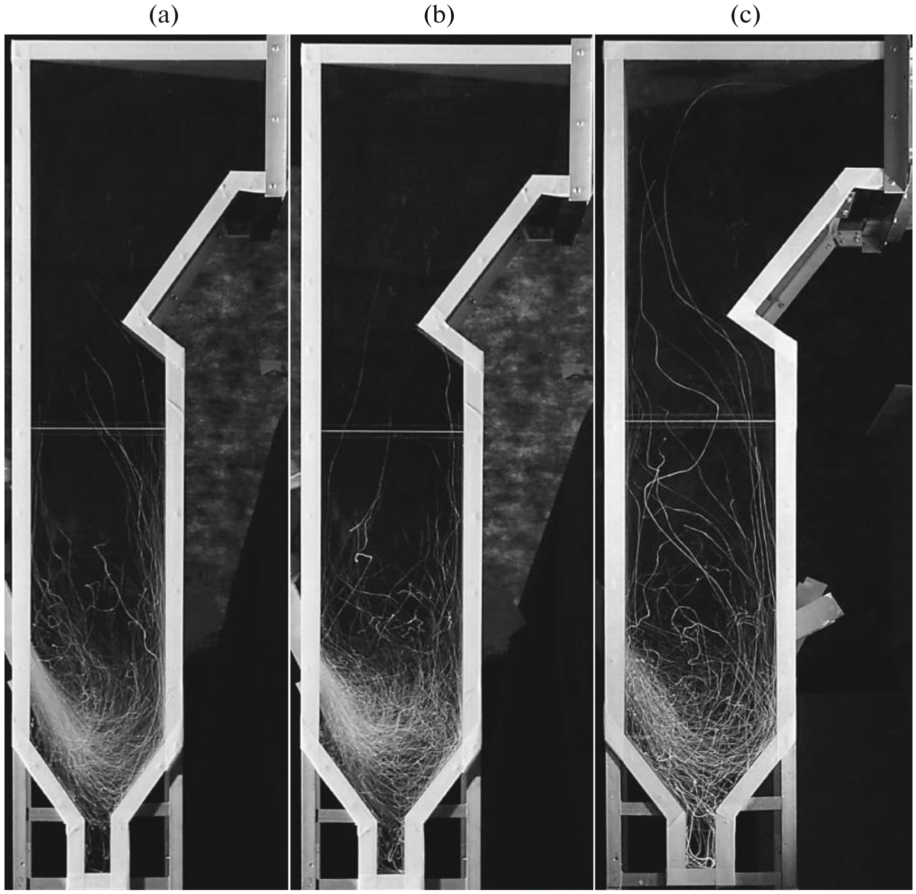

Fig. 3. PCB jet motion trajectories in section I–I: (a)—without restriction orifices; (b) with restriction orifices; and (c) with restriction orifices and closed GOBs.

conditions for stage-wise combustion of pulverized coal with low nitrogen oxide emissions are provided.

3. The version involving the use of closed GOB channels is not acceptable because (see Fig. 3c) unburnt particles fall on the dry bottom hopper slopes to cause the waterwall system becoming fouled and overheated. In the other considered versions, the location of the SOAN, TOAN, and GOB jets prevents coal and ash particles from falling on the dry bottom hopper slopes, walls, and in the boiler ash pit, thus making their surfaces less prone to fouling and wear.

4. The results from visualizing the flows obtained on the models with and without installing restriction orifices upstream of the PCBs have shown that their patterns differ insignificantly from each other. Hence, operational decrease of primary air flowrate will not affect the boiler performance results to any noticeable extent.

To determine the burner jet ejection capacity, investigations for clarifying the jet boundaries were carried out on the boiler physical model. Electrical heating of the flow going out from the burner model was used in the experiments. To this end, one of the burners was fitted with an electric heater made of nichrome wire. A 100-V voltage was applied to the heater from an autotransformer, and the temperature fields in the jet cross sections were measured by means of a chromel–copel thermocouple attached to a coordinate device. The coordinate device can be moved in three mutually perpendicular planes and was equipped with a rheochord for the possibility to convert the spatial coordinate into an electric current signal.

The signal from the precalibrated thermocouple in the form of a thermoemf and the current signal from the rheochord were applied to a digital multichannel recording device, which then transmitted the recorded data to a personal computer. Thus, the dependence of flow temperature on the coordinate related to the burner throat equivalent diameter was determined for each passage of the thermocouple in the horizontal section. The jet boundary was determined from a drastic growth of the thermoemf that was fixed by the recording instrument in passing the thermocouple. Velocities in the flow were measured by means of a Prandtl pneumometric tube, the impulse lines of which were connected to a digital differential pressure gauge.

Figure 4 shows the thermocouple readings in moving it across the model volume in the cases when the

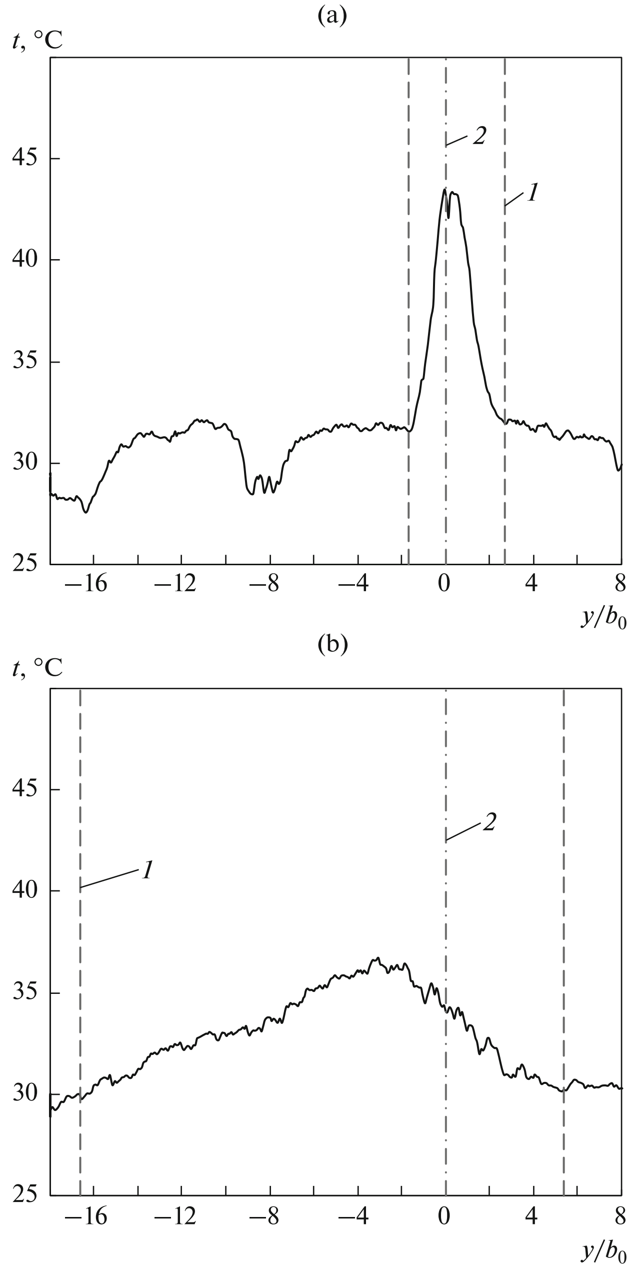

Fig. 4. Air temperature in the model versus the coordinate (a) near the nozzle and (b) at a distance away from the nozzle. *1*—Jet boundaries; *2*—burner axis.

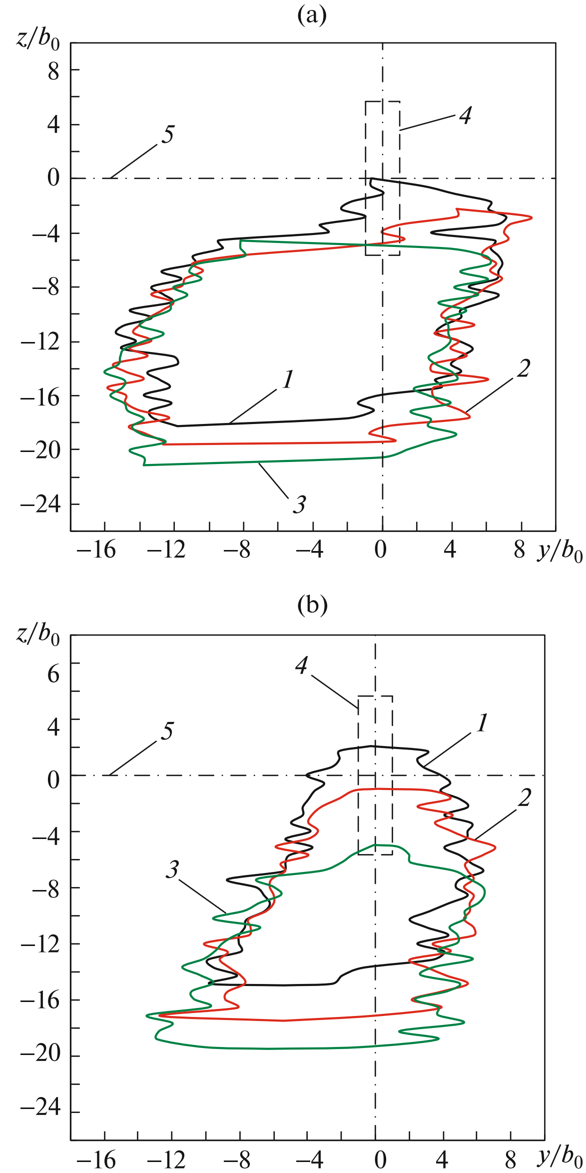

Fig. 5. PCB jet thermal boundaries in the model for the versions (a) with restriction orifices and (b) without them. *1*—$\bar{x} = 10.82$; *2*—$\bar{x} = 13.52$; and *3*—$\bar{x} = 16.23$. *4*—PCB throat outlines; *5*—PCB axes levels.

thermocouple passed the jet near the nozzle and when it was used for determining the boundaries at a distance away from the nozzle. The maximum flow temperature near the nozzle (see Fig. 4a) reaches 45–50°C; with distance away from the nozzle (see Fig. 4b), the temperature in the jet decreases due to the joined mass of surrounding air. A drastic rise of thermoemf shown by the multichannel digital recorder is used as the jet boundary indication. Approximately 30–40 thermocouple passes had to be performed to determine the boundaries for one jet section.

The boundaries of a jet flowing from a PCB were determined at eight sections along the jet axis. Figure 5 shows the thermal boundaries of jets flowing out from the pulverized coal burner in the coordinates related to the PCB nozzle half width (b_0) for three sections and for the operation mode versions with and without restriction orifices.

In the experiments carried out using the Prandtl tube connected to the differential pressure gauge, we determined the maximal and average values of velocities at the PCB nozzle exit in eight control sections of the jet and at the PCB nozzle exit. Based on the study results, the following graphic dependences have been

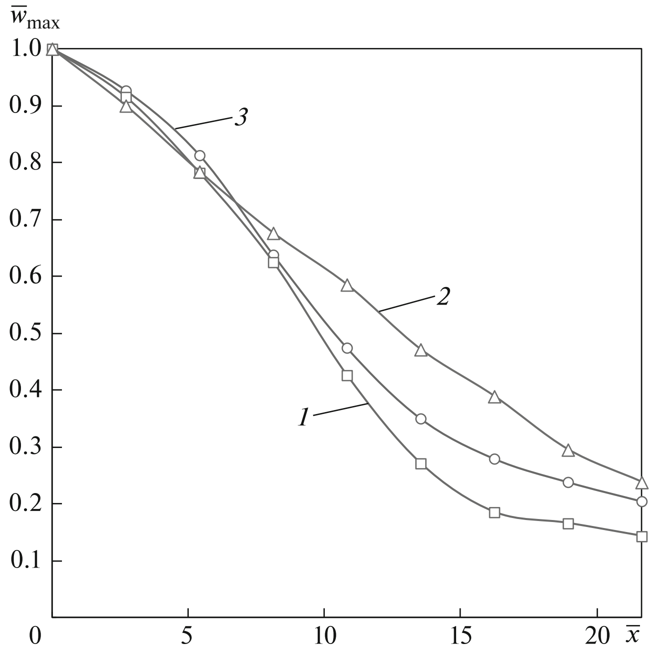

Fig. 6. Relative maximal velocities $\bar{w}_{max}$ along the PCB jet axis $(\bar{x} = x_l/b_0)$: *1*—with restriction orifices upstream of PCB; *2*—without restriction orifices upstream of PCB. *3*—GOBs are closed and restriction orifices are installed upstream of PCBs.

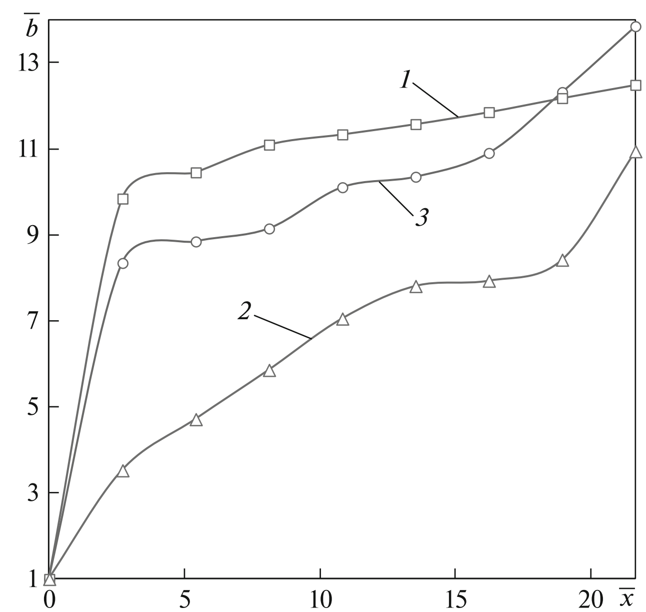

Fig. 7. Variation of jet section relative area with distance from the edge ($\bar{b} = F/F_0$ is the jet relative half width in the current section). The notation is the same as in Fig. 6.

constructed: variations of relative maximal velocities along the PCB jet axis (Fig. 6), ratios of the PCB jet areas in the current section to their areas in the outlet section (Fig. 7), and variation of the relative increment

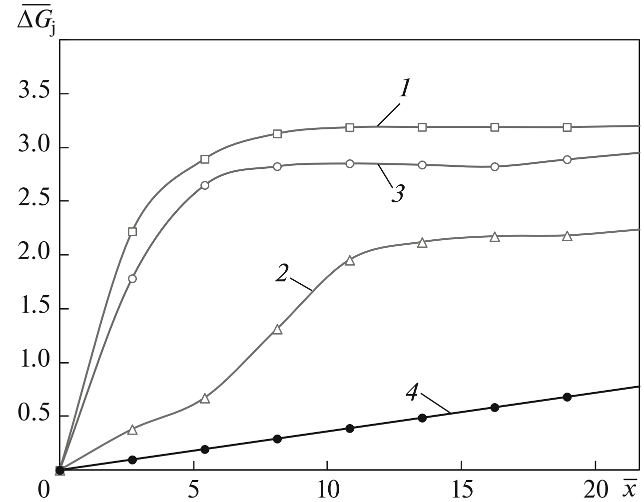

Fig. 8. Relative increment of PCB jet mass. The meaning of *1*–*3* is the same as in Fig. 6. *4*—for the submersed flat jet.

of PCB jet mass along the flow propagation axis (Fig. 8). For comparison purposes, Fig. 8 shows the dependence of relative increment of mass for a submersed flat jet at a uniform initial outflow velocity [5].

The following conclusions can be drawn from the graphic dependences obtained during investigations on the physical model. The PCB jets observed in all operation mode versions have hardly any initial part, which is attributed to high opposite resistance due to the motion of the opposite upward flow. It can be seen from Fig. 7 that the jets expand to a significant extent, and that their areas increase. In all studied versions (see Fig. 8), the jet mass increment is essentially larger than it is in the submersed flat jet. This is because the increment of mass in a fuel jet takes place not only due to ejection of the jet itself but also due to forced admission of furnace gases from other jets and from the furnace volume, i.e., by means of intrafurnace recirculation, which is generated owing to the tangential direction of all jets.

CONCLUSIONS

(1) Owing to arrangement of vertical vortices in the furnace lower part with a fairly large diameter making 0.55–0.60 of the furnace depth, it will be possible to efficiently use the ash hopper heating surfaces, to decrease the temperature of coal combustion products in the furnace upper part, and to obtain a smaller content of combustible substances in fly ash.

(2) Owing to the straight-flow burner body installed at a large downward slope (at 65°), it becomes possible to obtain a larger pulverized coal ignition diameter at the burner outlet, which should facilitate stable ignition of fuel.

(3) Tertiary overfire air jets prevent the combustion products with an increased content of harmful

substances produced due to incomplete combustion and unburned carbon of pulverized coal from freely leaving the vortex zones, thus facilitating more complete combustion of fuel and achieving smaller emissions of harmful substances.

(4) Due to setting up furnace operation with dry-ash removal and applying the proposed combustion arrangement with the use of straight-flow burners, longer motion trajectories of combustion products in the vortices are obtained, and a lower level of temperatures in the combustion zone is reached in comparison with the existing method of fuel combustion with liquid slag removal, which will make it possible to decrease the generation of thermal nitrogen oxides.

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