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STEAM BOILERS, POWER FUEL, BURNER DEVICES, AND AUXILIARY EQUIPMENT OF BOILERS

Efficiency of Using Direct-Flow Burners and Nozzles in Implementation of Dry-Bottom Ash Removal at the TPP-210A Boiler Furnace

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Abstract—In reconstruction of operating pulverized coal-fired boilers, one of the main factors is the choice of a method for slag removal: dry bottom ash removal (DBAR) or slag-tap removal (STR). In this case, ecological and economic aspects should be taken into account, and also the early ignition of pulverized coal fuel, the reliability of operation of the furnace walls in the mode without slagging, and the stability of slag removal should be provided. In this work, issues of changeover of the pulverized coal-fired boilers of the TPP-210A type from the STR mode to the DBAR mode are considered. As of today, the main problems during the operation of these boilers are the high emissions of nitrogen oxides together with flue gases into the atmosphere and the appropriated payoffs, a small range of loads available, the necessity of stabilization of the pulverized-coal flame sustainability by using the highly reactive fuel, large mechanical fuel underburning, etc. Results of studying aerodynamics of a furnace with DBAR obtained in the process of physical simulation are given; technical solutions and preliminary design (configuration of burners and nozzles in the boiler furnace, conceptual design of the pulverized coal burner, configuration of TPP-210A boiler with the low heat liberation of furnace cross-section and volumetric heat release) are set forth, which are associated with the optimization of aerodynamics of furnace volume, when the direct-flow burners and nozzles are used, and with organization of the efficient staged combustion of solid fuel. Two versions of possible modernization of a boiler unit are considered. Under conditions of the planned increase in the steam production capacity, the most promising measures are as follows: the DBAR implementation with reducing heat releases of the cross-section and volume of the furnace approximately by half, the installation of the direct-flow burners and nozzles with injection of recirculation gases into the active combustion zone by bleeding them from the turning chamber.

Keywords: boiler plants, dry-bottom ash removal, direct-flow burners and nozzles, mechanical fuel underburning, nitrogen oxides

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At the thermal electric power stations in Russia, the pulverized coal-fired boilers equipped with a system of slag tap removal (TPP-210A, TPP-110, P-50, TP-87, PK-40, etc.) are operated at the present time, in which sometimes the Kuznetsk coal of TR grade is used as a main or reserve fuel. In the years to come, replacing the overaged turbines of the T-250/300-23.5 type with the more modern turbine of the T-295/335-23.5 type is envisaged, which is required by the necessity to increase a steam-flow per turbine set; therefore a TPP-210A boiler should be reconstructed without sacrificing the height and transverse frame cell.

Fellow workers of the Moscow Power Engineering Institute (MPEI, National Research University) performed the investigation of operation of the TPP-210A, TP-87, and TP-80 boilers at the TETs-22 central heating and power plant (CHPP) of the PAO Mosenergo, a goal of which was to estimate a possibility of increasing a fraction of the TR-grade Kuznetsk hard coal to be burnt at them. At present, the natural gas cost exceeds the Kuznetsk coal cost by 25% in terms of the fuel equivalent with allowance for the cost of its delivery by railway transport from the site of extraction to central regions of Russia. In recent years, a growth in the cost of natural gas significantly has been ahead of a rise in the Kuznetsk coal cost; therefore, in the immediate future, it will be more cost-efficient for electric power plants to burn the coal. It was revealed that the main problems of operation of the TPP-210A twin-furnace boilers using the TR grade coal and the natural gas are as follows:

(1) Increased concentration of nitrogen oxides in flue gases when burning coal that reaches the value $C_{\mathrm{NO}_x} = 1800–1900$ mg/m^3 at a standard of 700 mg/m^3, according to [1], while for that new or reconstructed boilers is 570 mg/m^3.

(2) Necessity for stabilization of the pulverized coal flame by gas in order to provide a reliable exit of the liquid slag from slag-tap openings even at nominal load rating of the boiler.

(3) Narrow adjustment range of loads with the boiler's hard-coal-fired operation: $D_{\min} \geq 0.84D_{\text{nom}}$, where $D_{\text{nom}} = 500$ t/h is the nominal steam load and $D_{\min} = 420$ t/h is the minimal steam load of the boiler housing.

(4) Increased specific emission of nitrogen oxides into the atmosphere during the gas combustion ($C_{\text{NO}_x} = 300–350$ mg/m^3 at the standard of 125 mg/m^3 [1]) under conditions of full rate of gas recirculation fans (GRF).

(5) Need for constant clearance of territory of the existing ash-disposal area from ashes for the purpose of its life extension by means of its wider use in the building industry.

(6) Increased mechanical fuel underburning (combustibles in fly ash up to 3.0–3.5% at the standard of 2.0%) [2].

(7) Elevated temperature of exit gases and the increased electric energy consumption for draft and blast with the gas combustion due to GRF full loading, which is caused by the necessity for reducing a specific emission of NO_x.

For solving these problems, it was suggested to change the boiler operation over the DBAR mode with organization of the fuel-staged combustion using the direct-flow burners and nozzles [3]. The direct-flow burners are simpler and cheaper in fabrication, have lower aerodynamic drag (on average, 1.73 times less as compared with swirl burners), and are characterized with a larger degree of maintainability. Owing to the use of these burners and nozzles with organization of the fuel-staged combustion and optimization of furnace aerodynamics, we managed at some boilers to bring the nitrogen-oxide emissions to standard values, to expand the adjustment range of load, and to provide the slag-free mode of operation of the boilers [4].

The updated configuration of burners and nozzles (as compared to the one proposed in [3]) is presented in Fig. 1, design features of the burner are given in Fig. 2. To intensify the furnace-gas ejection into the tertiary air nozzle (TAN), it was decided to make the tertiary blast nozzles consisting of four tubes in the vertical course with minimum pure 100-mm piers between the neighboring tubes.

An ejection of medium into the system consisting of n jets, which outflow from cylindrical nozzles in the vertical course, can be compared with the ejection into a single jet that outflows from the cylindricalcal nozzle equivalent in area. With the fixed distance L, mm, from the nozzles, the following equations can be written [5]

for a relative flowrate in the n-jet system

$$\sum G_n \Big/ \sum G_{0n} = 0.155L/R_0; \tag{1}$$

for a relative flowrate in the single equivalent jet

$$G_{\text{eq}}/G_{0\text{eq}} = 0.155L/R_{0\text{eq}}, \tag{2}$$

where R_0 is the nozzle radius, $R_{0\text{eq}}$ is the radius of the equivalent nozzle, $\sum G_n$ is the total mass flowrate of the n-jet system, $\sum G_{0n}$ is the initial total mass flowrate of the n-jet system, G_{eq} is the mass flowrate of a single equivalent jet at the fixed distance L from the nozzle, and $G_{0\text{eq}}$ is the initial mass flowrate of a single equivalent jet.

From the condition of equality of an outlet area of the nozzles of n-jet system and the single equivalent nozzle, $F = \pi R_0^2 n = \pi R_{0\text{eq}}^2$, it follows that $R_{0\text{eq}} = n^{0.5}R_0$.

If we divide Eq. (1) by Eq. (2) and taken into account the equality of initial mass flowrates of the single equivalent jet and the n-jet system, i.e., $\sum G_{0n} = G_{0\text{eq}}$, then we can derive the following expression:

$$\sum G_n \Big/ \sum G_{\text{eq}} = n^{0.5}.$$

Thus, the ejection of combustion products into the n-jet system is more than into the equivalent jet by $n^{0.5}$ times. If the number of nozzles in the vertical course is $n = 4$, then the ejection of combustion products into the four-jet system will be twice as large as into the jet outflowing from the cylindrical nozzle of equivalent cross-section.

In order to speed up the pulverized-coal ignition, it was admitted as expedient to almost double a perimeter of close contact between the air mixture and furnace gases by installing vertical dividers in the burners (see Fig. 2).

By techniques stated in [4], an isothermal model of the TPP-210A boiler furnace has been calculated and fabricated, which is characterized by the configuration of burners and nozzles in accordance with Fig. 1. During model blowdowns, trajectories of motion of the burner and nozzle jets were obtained (Fig. 3). From Fig. 3, we can conclude that a motion of jets from the TAN occurs first with a small slope downward, then horizontally, after which they are carried out upward by the furnace gases that cross them; in this case, the interacting flows fill rather uniformly the furnace depth. Jets from the combined nozzle (CN) move with inclination downward at the depth of more than half the furnace depth, then they are directed upward along the opposed slope of the dry bottom hopper (approximately 85%, while the rest return under the jet root). Jets from the secondary air nozzle for flame adjustment (SANF) follow along the slope of the dry bottom hopper and emerge upward along the opposed slope. It has been revealed that aerodynamics of jets in the other even cross-sections of the furnace is roughly analogous, while it corresponds to the mirror reflection in the odd cross-sections of the furnace.

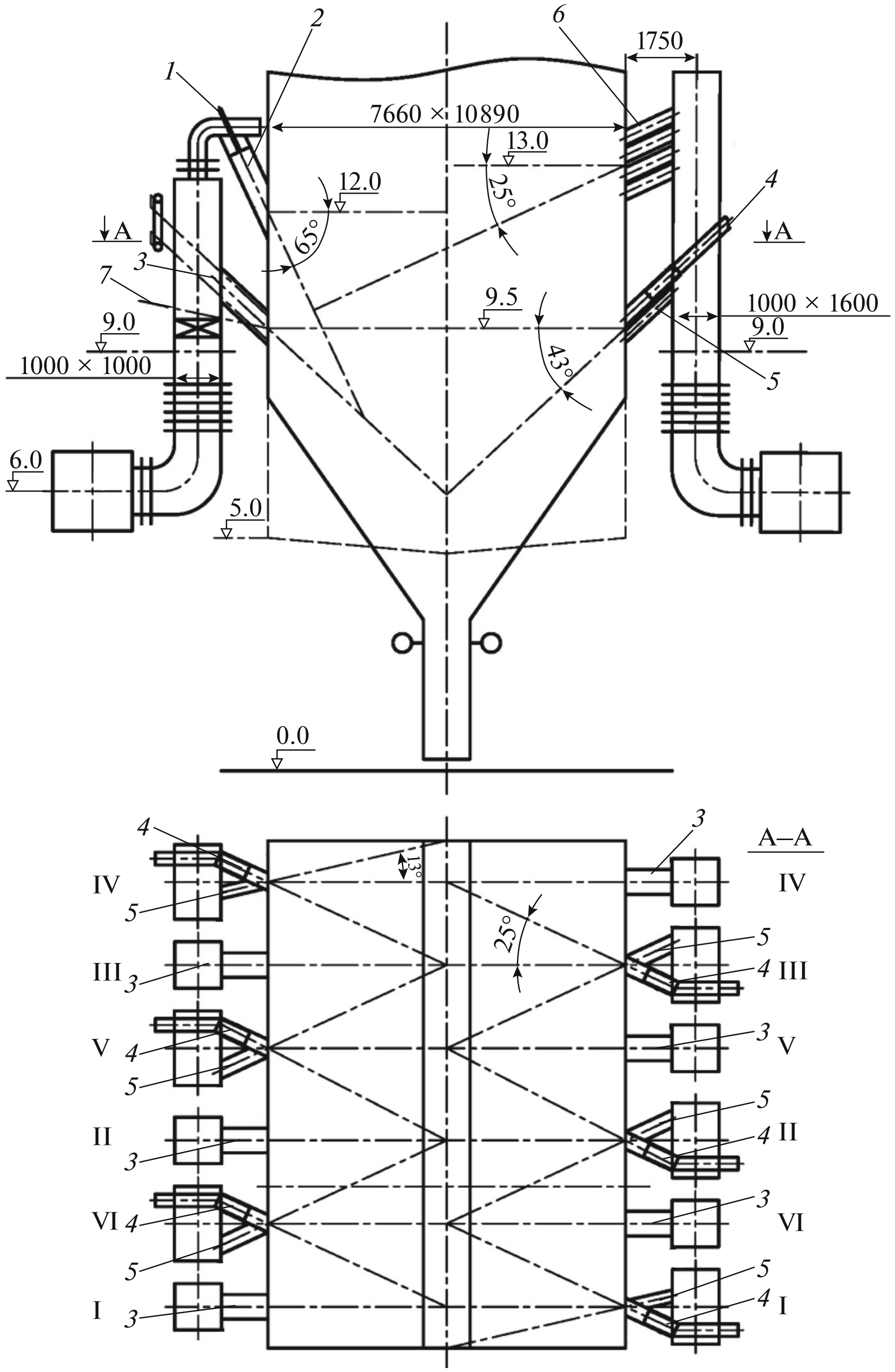

Fig. 1. Configuration of burners and nozzles in the furnace of the TPP-210AM boiler with DBAR: (*1*) pulverized coal of high concentration; (*2*) pulverized coal burner (PCB) (see Fig. 2); (*3*) secondary air nozzle (SAN) (oil-gas burner, see Fig. 2); (*4*) combined nozzle (CN), installed in section VI–VI: central channel of Ø377 × 5 mm (waste agent of pulverized coal system is supplied), outer channel of Ø530 × 7 mm (hot air enters through the ring channel); (*5*) secondary air nozzle for flame adjustment (SANFA), Ø265 × 6.5 mm; (*6*) tertiary air nozzle (TAN) (consists of four tubes of Ø325 × 7 mm, located one above the other in the general distribution of furnace-wall tubes); (*7*) axis of atomizer tube. Roman numerals from I to VI denote sections of the burners and nozzles arrangement.

Jets from the pulverized coal burner (PCB) and from the secondary air nozzle (SAN) move obliquely downward along the slope of the dry bottom hopper and rise upwards, mainly along its opposite slope. Some of the jets recirculate, entering to the PCB jet root from above. The upward egress of all jets occurs rather uniformly over the furnace depth in the mixture with tertiary air.

It should be noted that a lower part of the dry bottom hopper is filled with the flame. With the configu-

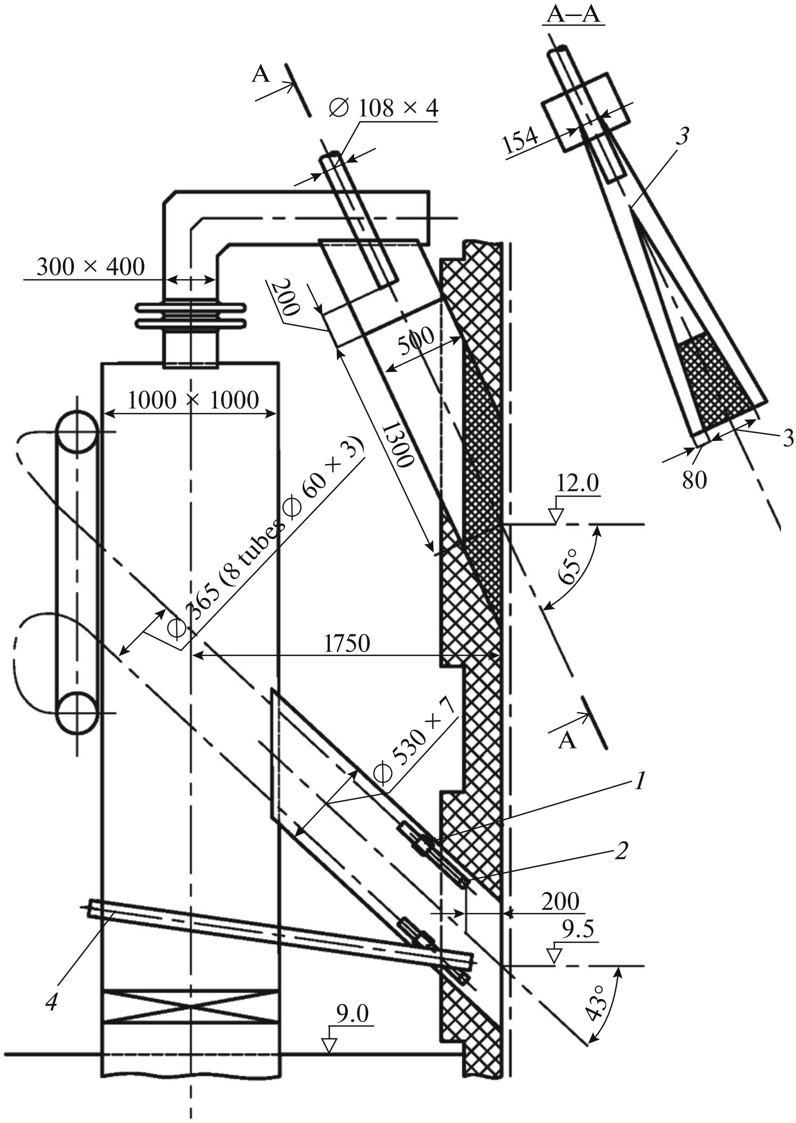

Fig. 2. Conceptual design of the pulverized coal burner and the secondary air nozzle (of the oil-gas burner): (*1*) sliding support; (*2*) gas orifice; (*3*) vertical impeller; (*4*) tube for mounting the oil-fired burner.

ration scheme under study, this causes the need for performing thermal calculations of the furnace, beginning from the cross-section of the narrow part of the dry bottom hopper, whereas the standards [2] recommend to perform these calculations beginning with a horizontal cross-section (middle in height) of the dry bottom hopper, taking into account the existing aerodynamics of flame with the opposed location of swirl burners.

The observed increased pressure of jets from CN, SANF, PCB, and SAN on the opposed slopes of the dry-bottom hopper is explained by the inertia of burning particles. Numerical simulation of jet aerodynamics using the software package of ANSYS Computational Fluid Dynamics has shown that these negative features of aerodynamics (zones of the increased pressure of the jets on slopes of the dry-bottom hopper) are absent. In this case, the computer simulation results should be admitted to be closer to a real combustion process, since the burning-out of inertial sawdust (used in physical modeling for visualizing a jet motion of burners and nozzles) is ignored in physical modeling. At the same time, a weak interaction of jets from PCB and TAN was revealed in the active combustion zone (ACZ), which can be explained by the increased heat release of the furnace cross-section.

By MPEI technique [4], according to which the air excesses are proportional to the cross-section of narrow places in burners and nozzles, a hot air distribution α_i over the TAN, CN, SANF, SAN, and PCB was

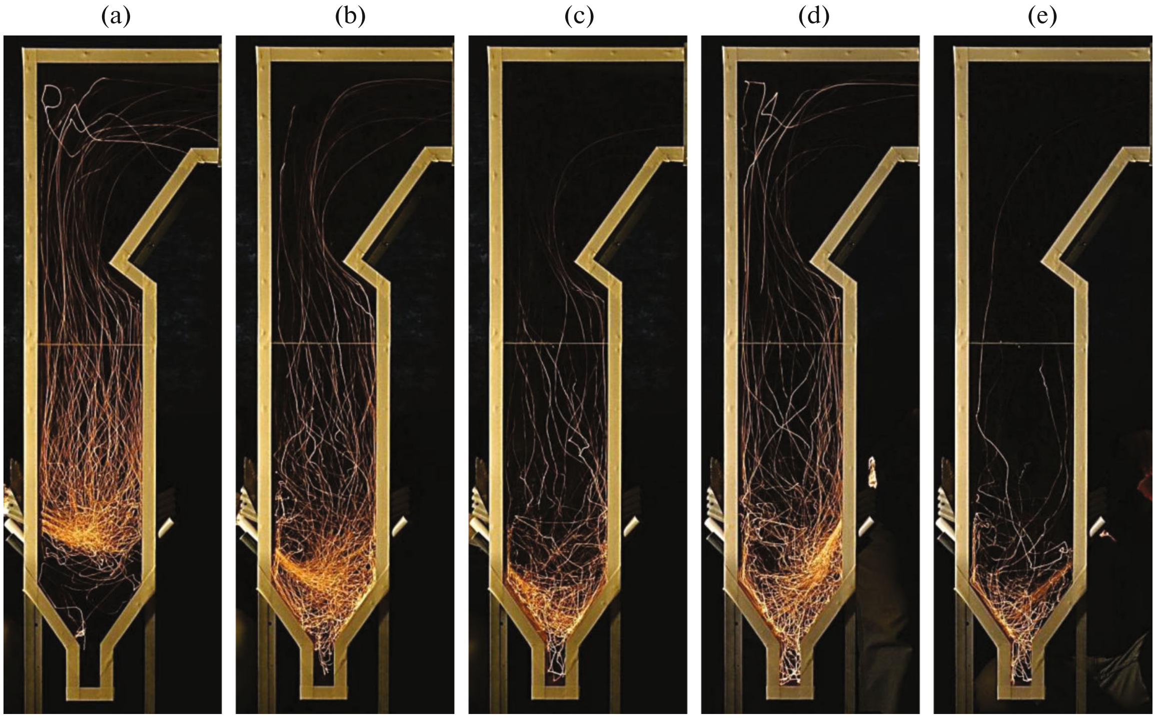

Fig. 3. Motion of jets of furnace devices in section VI–VI: (a) tertiary air nozzle; (b) combined nozzle; (c) secondary air nozzle for flame adjustment; (d) pulverized coal burner; (e) secondary air nozzle.

determined. With the air-fuel ratio at the furnace top of 1.15 and a supply of the waste agent of the pulverized coal system through the CN central channel with excess of 0.23, it has the following values:

Furnace devices	α_i
Tertiary air nozzle	0.366
Combined nozzle	0.1175
Secondary air nozzle for flame adjustment	0.1175
Secondary air nozzle	0.2175
Pulverized coal burner	0.082

Taking into account the jet motion nature revealed during the model blowdowns, the zone-by-zone calculation of the furnace was performed in accordance with the recommendations of [2]. The calculated temperature of furnace gases at the outlet from the first zone of the burners and nozzles arrangement at the adjustment mark of 14.5 m—with allowance for the increase in the boiler output (up to 515 t/h) and the elevation of temperatures of the fresh and secondary steams (up to 570°C)—amounted to 1634°C at the fuel burning-out degree of 0.95. At the outlet from the second zone with a height of 4.2 m, it was 1497°C at the fuel burning-out degree of 0.98. This testifies that furnace walls (especially the side ones) will be subject to slagging within the limits of the first and second zones. Slagging of furnace walls in the overlying zone also cannot be excluded. On the level of the exit gas window middle, the calculated gas temperature reduces down to 1105°C, which provides the slag-free mode of operation of convective heating surfaces (according to [2], at a temperature below 1070°C) with allowance for a heat release by wing walls and by railing of horizontal flue-gas duct.

The comparative efficiency of implementing the slag-tap removal at the TPP-210A boiler, when controlled-combustion zones of the front and rear walls of the furnace are absent, while its walls are pin-spaced and lined to an adjustment mark of 22.9 m (i.e., to a boundary of the third zone with a height of 4.2 m), has been analyzed. Adjustment marks of the TAN, CN, SANF, SAN, and PCB arrangement are accepted in accordance with Fig. 1. To increase a heating surface of the lined zone of the furnace, a tube bend of the furnace floor is located at the adjustment mark of 5.0 m instead of the existing mark of approximately 7.5 m. However, even under these conditions, a calculated temperature of furnace gases at the outlet of the third zone of the lined furnace walls was 1675°C with a temperature of 1216°C at the furnace outlet. These values, especially with the absence of the uninterruptible and reliable air-blowing of furnace-wall tubes, should be admitted to be extremely high.

The indicated disadvantages of operation of a TPP-210A boiler are caused to a great degree by the fact that the boiler manufacturer accepted the increased heat

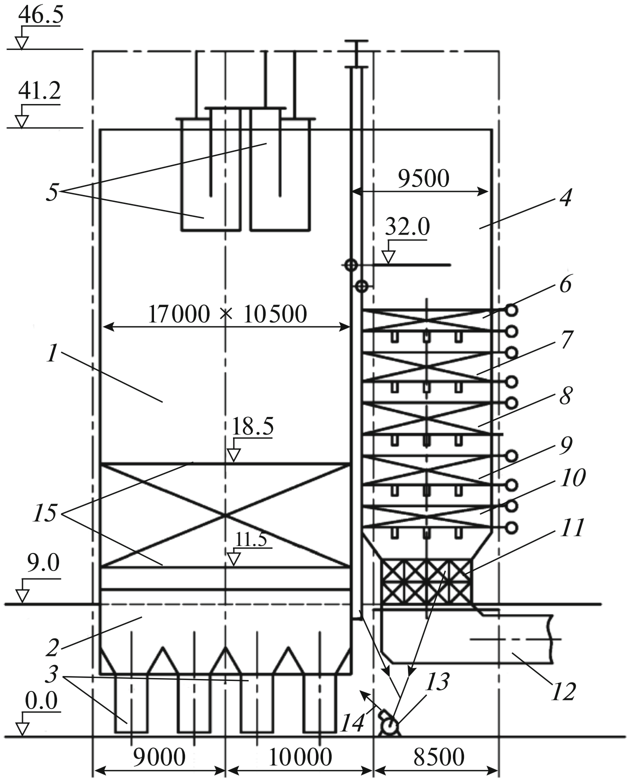

Fig. 4. Configuration of the TPP-210A boiler with low values of Q_F and Q_V: (*1*) furnace; (*2*) dry bottom hopper; (*3*) slag hoppers; (*4*) turning chamber; (*5*, *6*) wing walls and the convective fresh steam superheater; (*7*, *8*) high- and low-temperature secondary-steam superheater section; (*9*) gas-to-steam-steam heat exchanger; (*10*) water economizer; (*11*) tubular air re-heater with horizontal tubes; (*12*) flue-gas box; (*13*) gas recirculation fan; (*14*) toward the nozzles of the air and recirculation gases; (*15*) belt of the burner and nozzle arrangement.

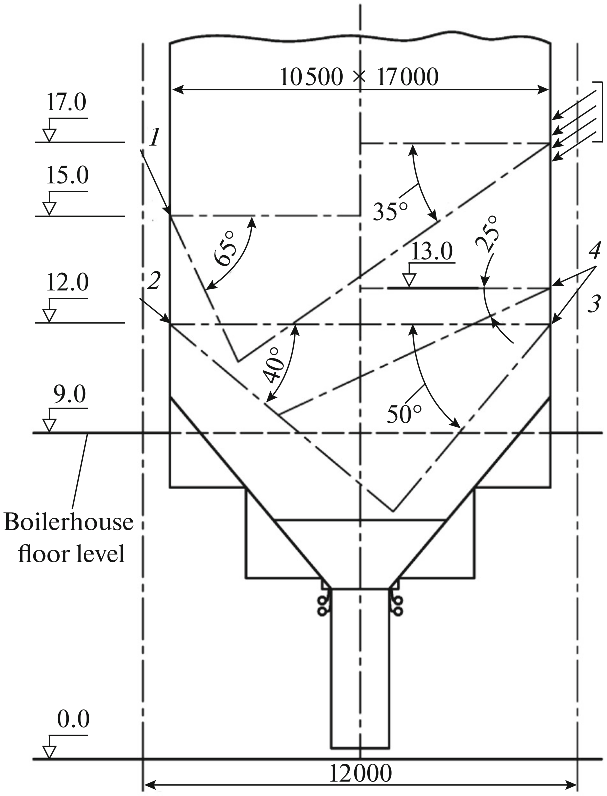

Fig. 5. Configuration of the burners and nozzles along the furnace height of the TPP-210A boiler with low values of Q_F and Q_V: (*1*, *2*) pulverized-coal and gas-oil burners; (*3*) nozzle of the air and recirculation gases; (*4*) combined nozzle; (*5*) tertiary air nozzle.

release of the furnace cross-section $Q_F = 5.05$ MW/m^2 and the volumetric heat release $Q_V = 147.7$ kW/m^3 for the load of 515 t/h.

Figures 4–6 present the more advanced version of reconstruction of the TPP-210A boiler of TETs-22 CHPP of PAO Mosenergo with the DBAR implementation. It is characterized by the significant decrease (approximately two-fold) in Q_F and Q_V. By results of the zone-by-zone thermal calculation of the furnace chamber with a degree of fuel burning-out at the outlet from the first, second, and third zones of 0.90, 0.97, and 0.98, respectively, the average temperature of flue gases at the ACZ outlet is 1434°C, while it amounts to 1078°C at the exit of the furnace chamber. Additionally, a specific feature of this version is that the recirculation of flue gases that are tapped from the turning chamber can be used during the hard coal combustion for providing slag-free mode of operation of furnace walls in the ACZ and the overlying zone of the furnace, which will not cause a noticeable increase in the temperature of flue gases. Despite the gas recirculation, the reliability and early ignition of the air and pulverized coal mixture owing to the more guaranteed forced supply of furnace gases to the roots of the air and pulverized coal jets under conditions of the increased perimeter of ignition due to the presence of vertical dividers at the PCB exit (see Fig. 2) is ensured.

In Fig. 5, a configuration of burners and nozzles located in one of the vertical planes is shown schematically for clarity. In the neighboring vertical planes, it corresponds to the mirror reflection.

Improving the slag-removal reliability and increasing up to 10–15% the ash fraction that enters into ash hoppers are guaranteed by a low heat release of the furnace cross-section, which leads to a reduction in temperatures in the combustion zone and to a decrease in the average speed of the ascending flow of flue gases by means of the downward inclination of the burners and nozzles and by the injection of recirculation gases with ash into the lower part of the dry bottom hopper. The staged combustion of fuels with a low fraction of the primary air will provide the stronger suppression of

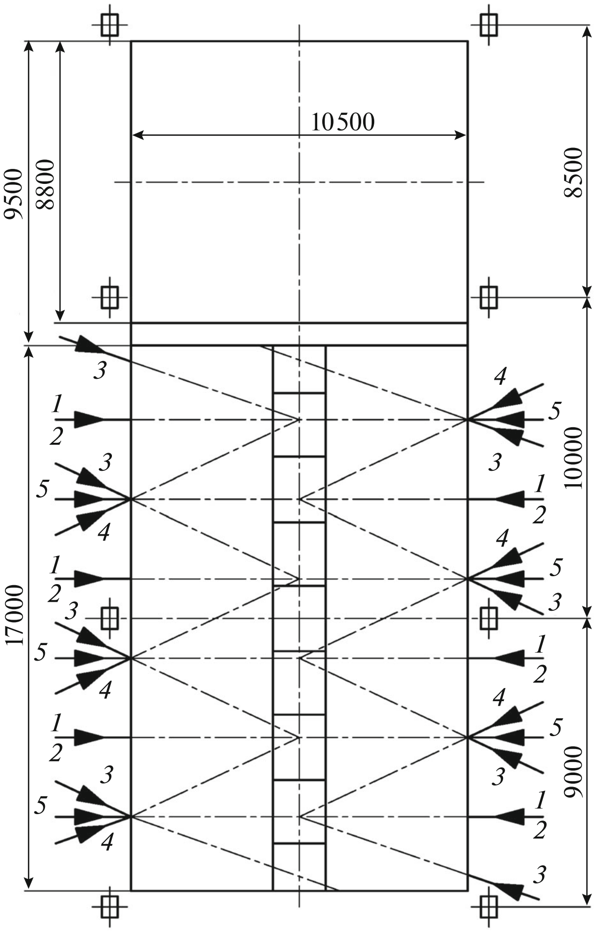

Fig. 6. Configuration of burners and nozzles across the width of side walls of the furnace of the TPP-210A boiler with low values of Q_F and Q_V. See designations in Fig. 5.

the combustive and "rapid" nitrogen oxides, amounting to 85–90% of the total emission. Creation of thermal nitrogen oxides, including those during the gas combustion, will be almost avoided owing to a low heat release of the furnace cross-section, the significant inner recirculation of furnace gases toward the roots of burner jets that contain unburnt combustibles, and also due to injection of outer recirculation gases into the ACZ. Fabrication of a tubular air reheater with horizontal tubes blown with flue gases will ensure the reliable work of the blasting equipment (not shown in Fig. 4).

Figure 7 shows the experimental dependence of the complex efficiency of operation of pulverized coal-fired boilers E_b on the mode-constructive (complex) parameter of ignition K_{ig} [3, 4], which is calculated by the equation

$$K_{ig} = (P_0/P_{hfc})\left(V^{w}/V_{h}^{w}\right)\Big/\alpha_b\,, \tag{3}$$

where P_0 and P_{hfc} are the total perimeter of the close (convective) contact of the air and pulverized coal mixture with furnace gases at the burners' throat pressure part and the perimeter of the horizontal furnace cross-section, respectively; V^{w} and V_{h}^{w} are the volatile content in the burnt coal, calculated for its working mass, and the standard content in the hard Kuznetsk coal, respectively; α_b is the coefficient of air excess at the outlet of burners.

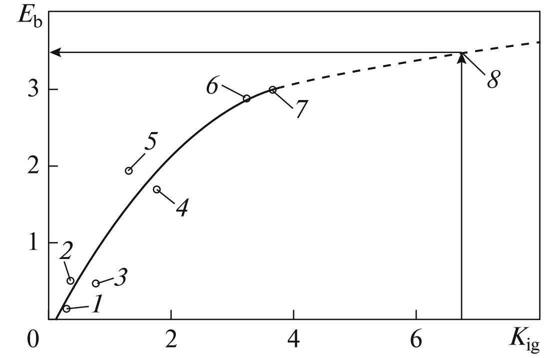

Fig. 7. Experimental dependence of E_b on K_{ig}: (*1*) TPP-210A boilers of TETs-22 CHPP of PAO Mosenergo with STR, coal of TR grade; (*2*) PK-10 boilers of Yuzhno-Kuzbasskaya regional hydro-electric power plant (RHEPP) with DBAR, coal of TR grade; (*3*) BKZ-220-100F boiler (no. 17) of the Kuznetskaya CHPP, coal of GR grade; (*4*) BKZ-210-140F boiler (no. 6) of the Zapadno-Sibirskaya CHPP with DBAR, coal of GR grade; (*5*) TP-10 boiler (no. 7) of Tom-Usinskaya RHEPP with DBAR, coal of GROK grade; (*6*) BKZ-210-140F boiler (no. 5) with DBAR, coal of GR grade; (*7*) K-50-14-250 boiler (no. 2) of the boilerhouse of the town Tashtagol, coal of GR grade; (*8*) TPP-210A boiler of TETs-22 CHPP of PAO Mosenergo with DBAR, coal of TR grade.

The complex factor E_b is offered to be estimated as a product of three relative factors [3, 4]:

$$E_b = \left(q_4^{s}/q_4^{r}\right)\left(\mathrm{NO}_x^{s}/\mathrm{NO}_x^{r}\right)\left(D_{nom}/D_{min}\right), \tag{4}$$

where q_4^{s} and q_4^{r} are the standard and real mechanical unburnt fuels, respectively; NO_x^{s} and NO_x^{r} are the standard and real concentrations of nitrogen oxides in flue gases.

As a result of extrapolation (point *8* in Fig. 7) with allowance for Eq. (4), the following expected values were determined, which characterize the efficient performance, ecological efficiency, and reliability of operation of the TPP-210A boiler of the TETs-22 CHPP of PAO Mosenergo after its reconstruction, according to Figs. 4–6:

(1) mechanical unburnt fuel $q_4 = 1.6\%$ at the standard of 2% (for DBAR) [2]; nitrogen oxide concentration $C_{\mathrm{NO}_x} = 450$ mg/m^3;

(2) minimum load of boiler housing by condition of reliability of pulverized coal combustion without stabilization of flame sustainability by gas is 195 t/h.

Thus, the most promising solutions in reconstruction of the TPP-210A boiler of the TETs-22 CHPP of PAO Mosenergo in connection with the planned installation of the leading turbine of the T-295/335-23.5 type are as follows: (1) implementing the dry bottom ash removal, (2) mounting the direct-flow burners and nozzles, (3) injecting the recirculation gases in the ACZ with tapping them from the turning chamber.

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