Part 4

COMPLEX TECHNOLOGIES OF REDUCTION OF ENVIRONMENTAL POLLUTION FROM THERMAL POWER PLANTS

4.3. Combustion of solid fuel

4.3.4. Improving the reliability, maneuverability and environmental safety of K-50-14-250 boilers at coal burning by optimizing the furnace aerodynamics

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1. SHORT DESCRIPTION AND MAIN DRAWBACKS OF THE K-50-14-250 STEAM BOILER OPERATION BY FUELS COMBUSTION WITH THE VORTEX BURNER USE

In the production-heating boiler-house of the city Tashtagol (Kemerovo Region), related to Yuzhno-Kuzbasskaya Energy Company, LTD five K-50-14-250 boilers are installed. They are designed for hot water supply of the city and net output of steam for iron ore extraction mine.

Steam double-drum vertical water-tube K-50-14-250 boilers with natural circulation, produced at Belgorod boiler factory, have a П-shaped layout and are designed for coal dust combustion. Originally the boilers were designed to burn natural gas and sour oil, however, they were reconstructed by the factory for burning hard coal. The main operating parameters of the boiler are the following: nominal steam rate $D_{nom} = 50$ t/h, temperature of steam superheating $t_{ss} = 250\ ^{0}$C (feed water temperature $t_{fw} = 104\ ^{0}$C), pressure of the superheated steam $p_{ss} = 14$ kgf/cm^2. Before reconstruction all boilers had four opposite-located vortex burners of snail type, placed by two on side walls of the combustion chamber. Tubular air heater and economizer have two stages. At the combustion chamber outlet there's a screen, in the horizontal gas duct the superheater and convection bank are located. The last is the evaporating surface of a small drum. To collect ash, wet ash collectors – scrubbers are installed. The boiler is equipped with one smoke exhauster and one blow fan.

In the boiler Kuznetsky hard coal of grades G (gas coal), GR (gas ordinary coal), D (long-flame coal) and DRSSH (long-flame ordinary kernel burgy coal) is burnt. These coal grades are extracted from different sections and have different calorific values, volatile content, moisture and ash content.

Coal dust is prepared using two jar rollers and two mill fans (for each boiler) with its direct injection into the furnace. At the boiler-house the following normative values, characterizing particle size distribution of the fuel, are accepted: $R_{90} = 18$ %, $R_{200} = 2$ %.

The boilers operate in a mode of solid slag removal. The boiler throat slopes are located along the front and back walls of the furnace. The boiler furnace is completely screened by pipes of 60°mm in diameter, arranged every 70 mm.

Longitudinal section of K-50-14-250 boiler before reconstruction of the furnace-burner units is shown in Fig. 1.

The main disadvantages of operation of K-50-14-250 boilers as built (before modernization) [1] are as follows:

- unstable combustion of coal dust without lighting the flame by highly reactive fuel - fuel oil under reduced load (in case one mill is under operation), leading to significant overexpenditure of expensive fuel;
- high temperature of combustion products after the boiler bank, which reduces reliable operation of the uncooled ceiling above the turning chamber and upper tube plates of the second stage of the air heater;
- high temperature of flue gases, reaching 165…170°C, which helps to reduce the boiler efficiency;
- increased value of mechanical fuel underburning; so combustibles in fly ash reach 30-40°% at the standard level of 14°%;
- nitrogen oxides concentration in flue gases is 800…850 mg/m^3, which is 1,7…1,8°times as high as the normative value set by the State Standard (GOST) (470 mg/m^3 for dry bottom boilers) [2].

During the summer period at significant reduction of the need in hot water supply in the cities and under conditions of poor fuel combustion at reduced loads, the staff of the boiler-house had to stop operation of the boiler from time to time.

Main reasons for the instable combustion are as follows:

- Under conditions of using snail-type burners with the peripheral stream of secondary air and the central stream of air mixture there is a surface of direct early contact a coal dust with flue gases being insufficient for reliable ignition (one can say that the contact is missing). Ignition occurs due to the presence of a reverse current zone [3], power of which is not enough. In case one grinding mill is off (under operation conditions or repair) the surface of this contact is twice less, which sharply reduces the stability of the coal dust ignition.
- The disadvantage of technological ignition is associated with a relatively low temperature of flue gases. K-50-14-250 boilers are dry bottom ones. They have a low thermal stress of the furnace cross-section (1,343 Gcal/m^2·h) and insufficiently high temperature of gases in the flame core (1350-1450°°C).
- Waste drying agent exhausted at K-50-14-250 boiler with a temperature of about 60^{0}C together with coal dust and evaporated fuel moisture comes directly into the ignition zone and cools it.
- Wear of the flow channel of fuel mixture snails, which happens in boilers of Tashtagol boiler-house, helps to reduce the opening angle of the fresh air mixture jet, which reduces reliability of the coal dust ignition. This is compounded by the fact that the burners at the outlet of fuel mixture channels have no bell mouths, i.e. initial perimeter of ejection (ignition) is comparatively small.

The above reasons for unsatisfactory performance of K-50-14-250 boiler of Tashtagol boiler-house have prompted the authors of the paper to deal with design and implementation of a new scheme of combustion of Kuznetsky coal in direct-flow vortex flame.

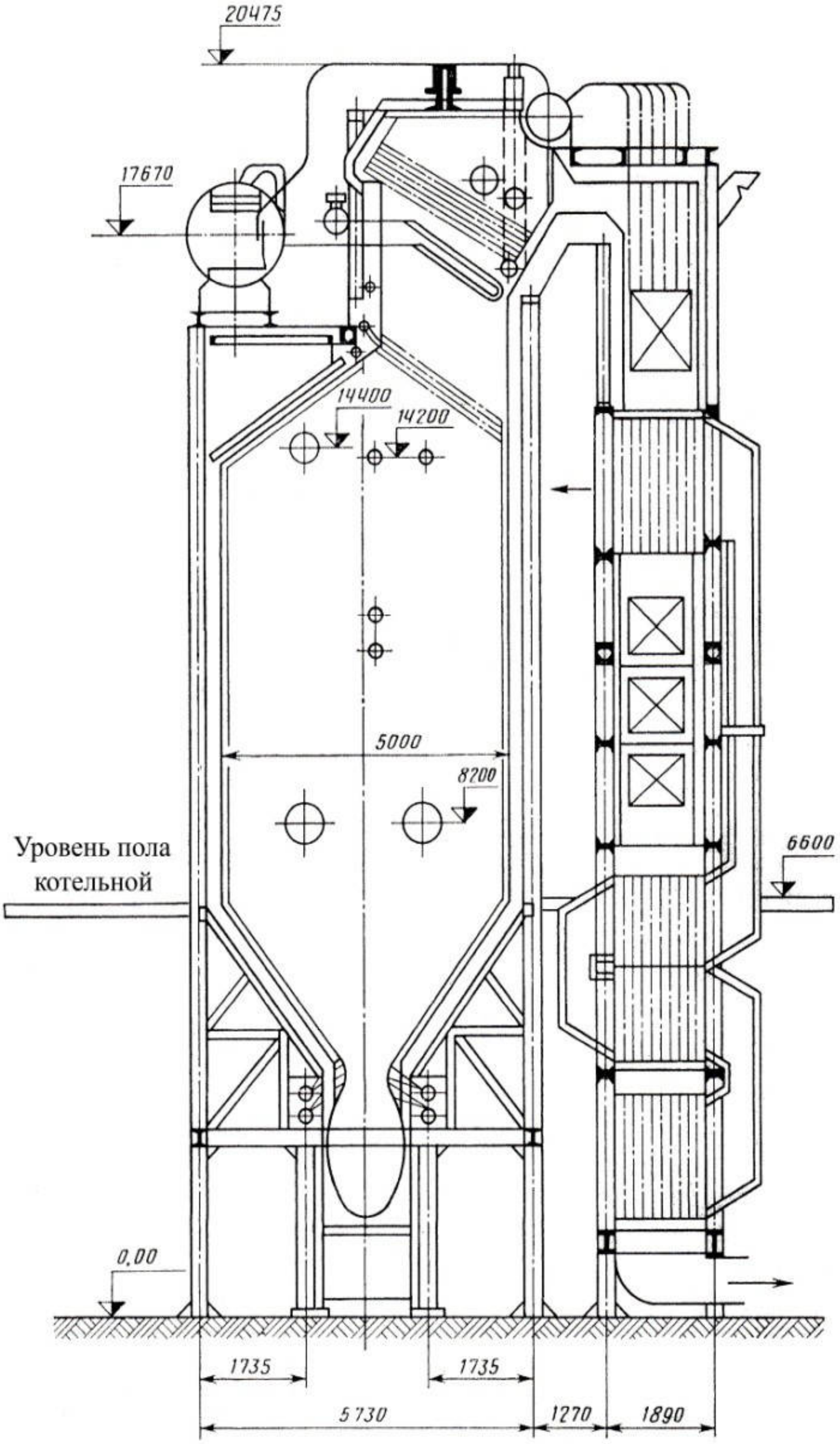


Fig. 1. **Longitudinal section of the steam K-50-14-250 boiler with vortex burners.**
Note: Уровень пола котельной - floor level of the boiler-house.

2. DEVELOPMENT OF TRANSITION COAL BURNING SCHEMES IN A U-SHAPED DIRECT-FLOW VORTEX FLAME

2.1. Furnace aerodynamics scheme and its research on the model applied to the boiler №2

The developed scheme of furnace aerodynamics under conditions of direct counter-shifted streams, shown in Fig. 2, is a fuel combustion scheme in the system of vertical and horizontal tangential flares (VHTF). In the Fig. the following conditional symbols are considered: Г°–°direct-flow burner, CBB°–°secondary air nozzle, CTB°–°tertiary air nozzle, numerals indicate the numbers of nozzles and burners. Along the height of the combustion chamber the oxidant is stepwise supplied to the burning fuel jet due to nozzles of the secondary and tertiary blast. Structurally, the direct flow burner is made as a pipe Ø426×7 mm, having a downward inclination by 45^0, in the inner part of which dust spreaders are set. The burners are installed at the level of 11 m. On the opposite side furnace wall (in a plane of burners location) nozzles of secondary and tertiary air are installed. Secondary air nozzles Ø426×7°mm are placed horizontally at the level of 7,1°m. The central channel of the secondary air nozzle is a pipe where fuel oil nozzle of spray steam is set. Tertiary air nozzles of Ø219×7°mm are arranged by height between the burner and the secondary air nozzle (9,5 m mark) and are intended for additional turbulence of tail volumes of burner jets and increase in the oxidant concentration at the stage of fuel afterburning. At the same time it was taken into account that this arrangement should provide a relatively low position of the core flame and reliable fuel flow turbulence by fresh burner jets and fresh tertiary air jets. Airbag of secondary blast jets should prevent from falling out the unburned dust in the ash hopper.

The jet velocity at the outlet of the secondary air nozzles (in case of full opening the shutters before them) and tertiary air nozzles in case of two operating grinding-mills will make about 17,5 m/s. Shutters before the secondary air nozzles can partially close down to increase exhaust velocity of tertiary blasting jets in order to intensify turbulence in the dying flame.

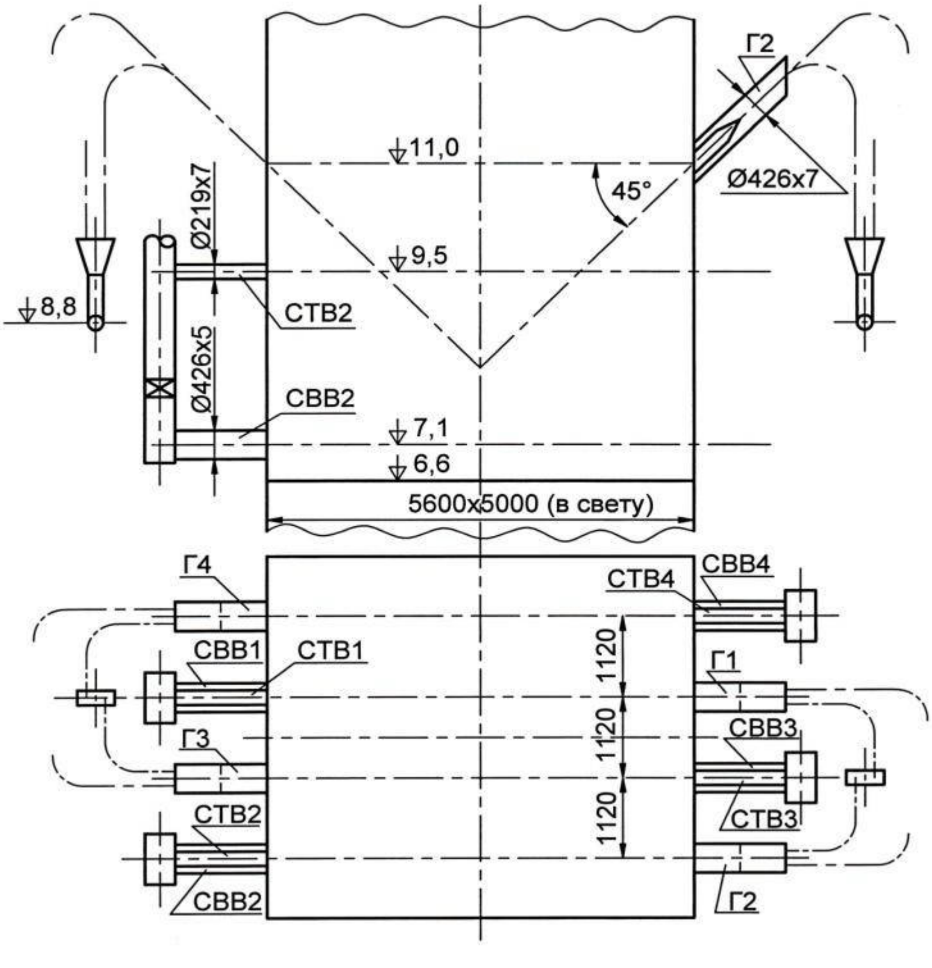


Fig. 2. **Location of straight-flow burners, secondary and tertiary air nozzles at the boiler №2.**

At the output of the burners setting of flow fuel mixture dividers with the size of 192 mm were envisaged. This engineering solution is designed to provide a zone of reverse currents in order to increase the stability of the coal dust ignition. Due to this, the initial ejection perimeter increased by 25 % and amounted to 6,84 m (for four burners). The exhaust air mixture velocity will make 26,9°m/s (D_{nom} = 50 t/h, two grinding-mills are on) and 15,9 m/s (D = 30°t/h, one grinding-mill is on).

Fig. 3 shows the layouts of construction of straight-flow burners, secondary and tertiary air nozzles.

Fuel oil atomizers are inserted into the secondary air nozzles at a slight angle to the nozzles axis. They have short trunks (less than 1,2 m) and are served at the same area (6,6 m mark).

Dust dividers are designed so that coal dust is supplied in all direct-flow burners in case one mill is in operation. Before reconstruction when one of the grinding mills is turned off, there were only two out of four swirl burners in operation. The last is also one of the reasons for the unstable fuel combustion at reduced loads.

Arrangement scheme provides lower-side forced supply of flue gases in fresh burner jets, which solves the problem of sustainable ignition. By that it is important that it's not needed to warm up rather large masses of secondary air that takes place in the existing burners of K-50-14-250 boiler.

The increased value of the internal flue gases recirculation, containing underburning products, into fresh burner jets, as well as the dispersal of afterburning flare zone will reduce specific NO_X emissions to the normative level – 470°mg/m^3 [2].

The important role of tertiary blasting is the turbulence of flame, rising up. Tertiary air excess should be about 0,1 at rated exhaust velocity not less than 17,5 m/s. To provide higher speed, partial closing of air shutters before the secondary air nozzles is required.

The following provisions make a basis for the option for further development:

1. Using direct-flow burners instead of vortex ones provides a better filling of the furnace volume and more reliable control of the trajectory of their flame flow.
2. Rise to a higher level and burner slope down provides an increase in the available length of the generalized flame. Under conditions of increased primary air consumption (due to high cold air inflow in coal-pulverization system) this principle of arrangement makes more complete use of kinetic energy directed obliquely downward air mixture jet for better ignition and mixing of reagents (due to oncoming flow the air mixture moves obliquely downwards, and combustion products - up).
3. Separate (from the secondary and tertiary air) input of air mixture jets to the furnace contributes in their more rapid heating, ignition and reduction of the NO_X formation [4].
4. The use of four dust dividers allows to keep the number of burners (four pieces), regardless of the number of working grinding-mills. This allows to increase the stability of coal dust ignition with one operating grinding-mill and to eliminate the need for switching on the oil nozzles while reducing the boiler load. Each divider consists of a lower inlet of Ø273x7°mm and two upper outlets of Ø219x7 mm. Before each burner a special adapter-mixer is installed. It is linked with two dust lines of Ø219x7 mm – one from each divider belonging to different grinding-mills.

Increase in dust flue resistance due to new sections will not occur, because there are no snails before the burners. On the contrary, it is estimated that the dust flue resistance will drop by 18 kgf/m^2. There is a possibility to increase ventilation of working grinding-mill and its additional fuel loading.

5. The layout scheme of Fig.2 provides the aerodynamics of the U-shaped flare, which is well recommended at five reconstructed BKZ-210-140FD boilers of Zapadno-Sibirskaya CHPP [5 and 6] (without lightning the flame at the load range of 210…140 t/h combustibles in fly ash significantly reduced as well as nitrogen oxides). In addition, heat reception by superheater also decreased.

This technology is changing if applied to furnace with smaller wall dimensions and side placement of the burners. It can be realized under conditions of counter-shifted and downwardly sloping arrangement of nozzles and burners (Fig. 2).

To investigate the furnace aerodynamics of K-50-14-250 boiler while burning fuel in a U-shaped direct-flow vortex flare (at counter-shifted arrangement of burners and nozzles), an experimental plant was developed and created. It's picture is shown in Fig. 4.

The model scale was taken as m = 1:23,42. Aerodynamic model of the furnace repeats the main design features of the boiler furnace chamber.

The results of spark blowdown of the burners, nozzles of tertiary and secondary air are shown in Fig. °5-7.

The fuel-air jet (Fig. 5) before the middle of the furnace model moves downward at an angle close to the angle of setting the burners and with small extension. Somewhere from the middle of the model width of the furnace it's seen a significant expansion and deceleration of the burner jet, which demonstrates its active interaction with the secondary air stream. Thus, we can conclude about the jet warming up, ignition of volatiles and external fuel afterburn in the area until the middle of the furnace. Active fuel combustion along the whole section of the fuel and air jet at an increase in the excess air and its significant turbulence takes place in the area of the jet from the second half of the furnace width. Availability of the coal dust divider in the burner promotes more uniform distribution in the output embrasure part and heats the jet from the inside (between the two parallel air-fuel mixture jets) due to ejection in the beginning of its movement.

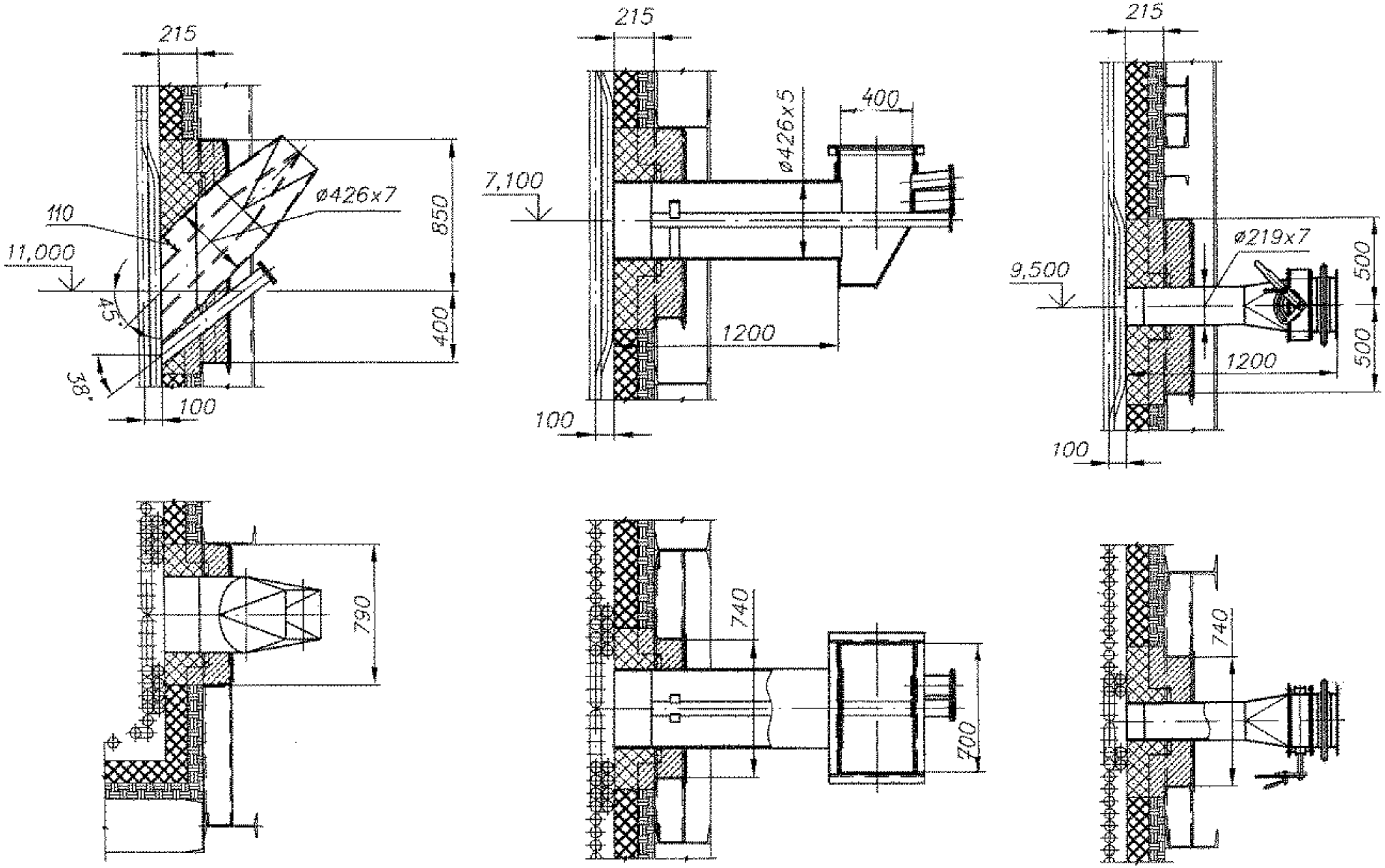
Relatively high location of duct burners and a large tilt angle leads to the rapid warming of jets and reduction of the combustion products temperature at the furnace top due to the longer path of burning fuel particles.

If we simultaneously compare the flow pattern of all burner jets, one can see the idea of how the flame core disperses through the furnace width and depth and its location is somewhere in the middle between the levels of CBB and CTB.

In addition to the secondary air supply to the burner jet, CBB performs the function of shielding the side wall from direct breakthrough of the fuel-air jet. Due to this, there is a reduction and an alignment of the local thermal loads on the furnace screen surface, which reduces the probability of furnace walls slagging. Airbag, which arises at secondary air motion, in large extent prevents from the falling out (separation) of the coal dust particles into the boiler throat due to centrifugal forces (Fig.6).

Tertiary air (Fig. 7) is reaching the fuel jet in the later combustion stages and additionally turbulizing it. While fuel particles afterburn it is important to provide the necessary excess air for the maximum complete combustion of the fuel particles.

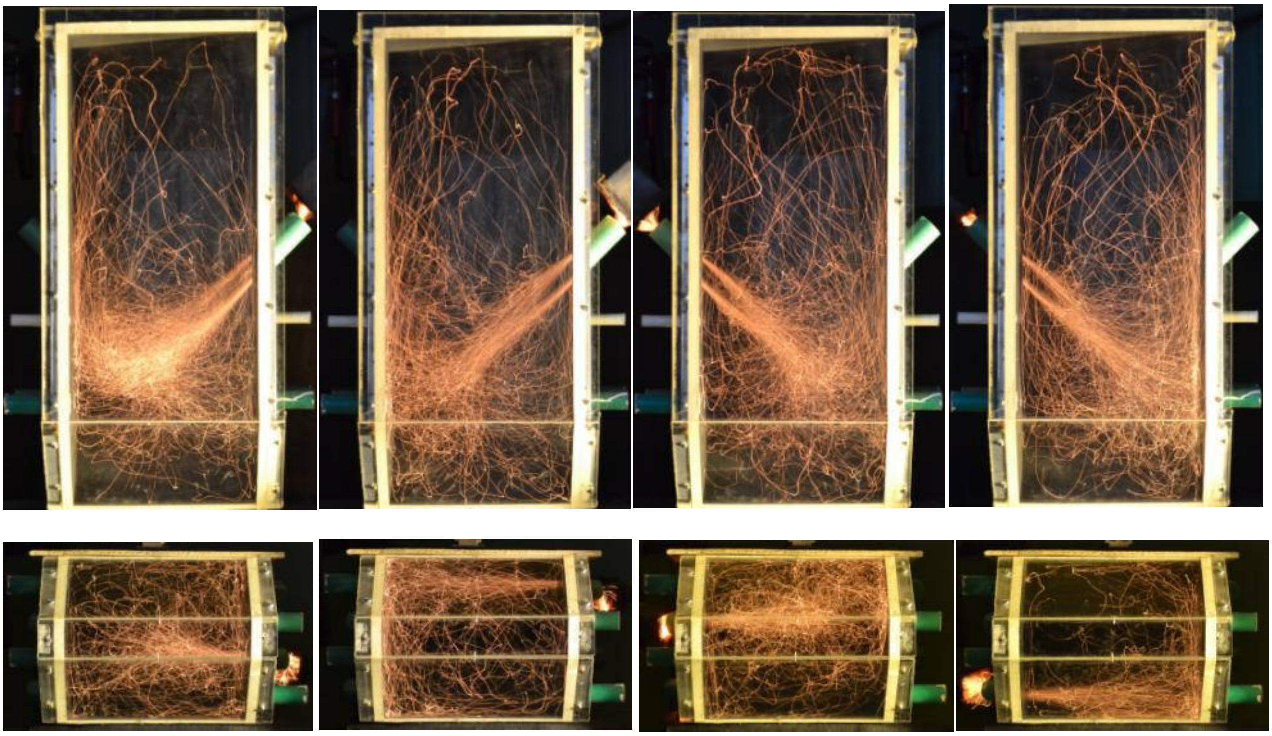
It can be concluded that blowdown gives a significant inside-furnace recirculation of the hot flue gasses into fresh fuel jets, an earlier fuel warm up and an active afterburn when it contacts the secondary and tertiary air jets.



a) b) c)

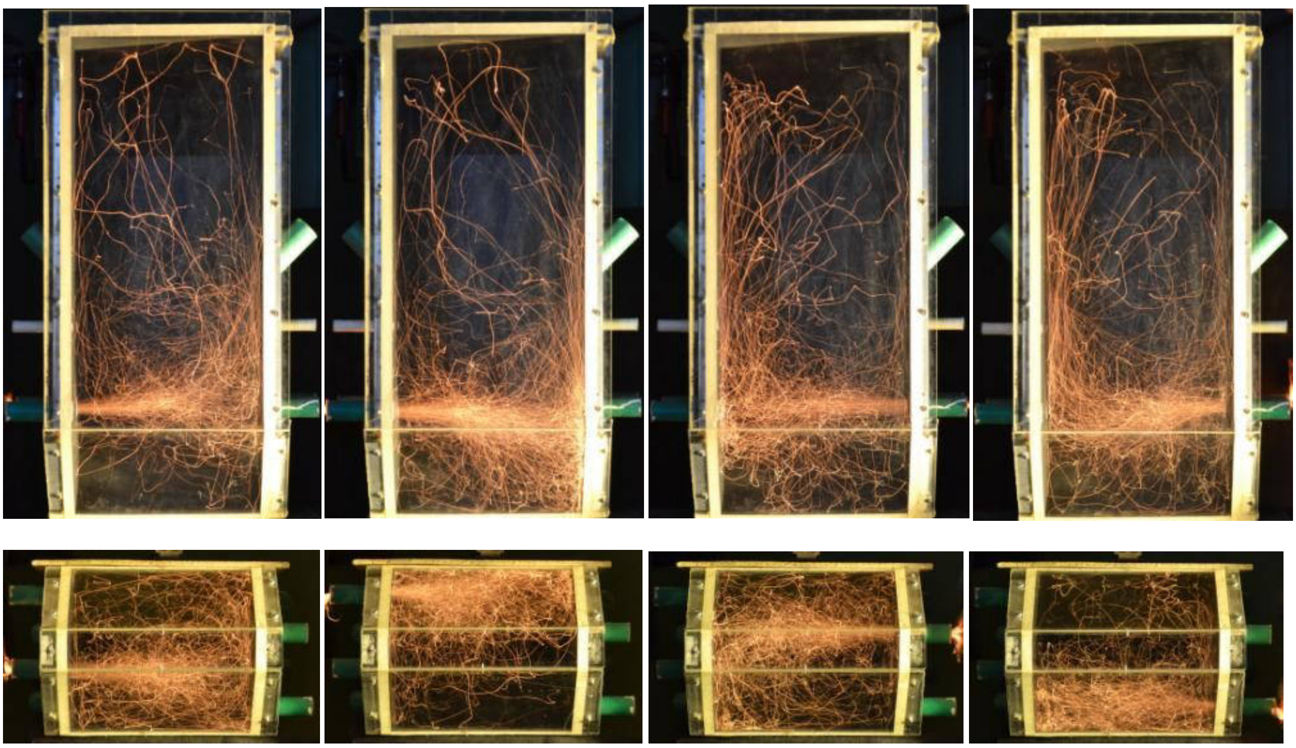
Fig. 3. **Schematic design of burners and nozzles:** a) burner; b) secondary air nozzle; c) tertiary air nozzle**.**

Fig. 4**. General view of the experimental plant for studying the furnace aerodynamics at the boiler №2**



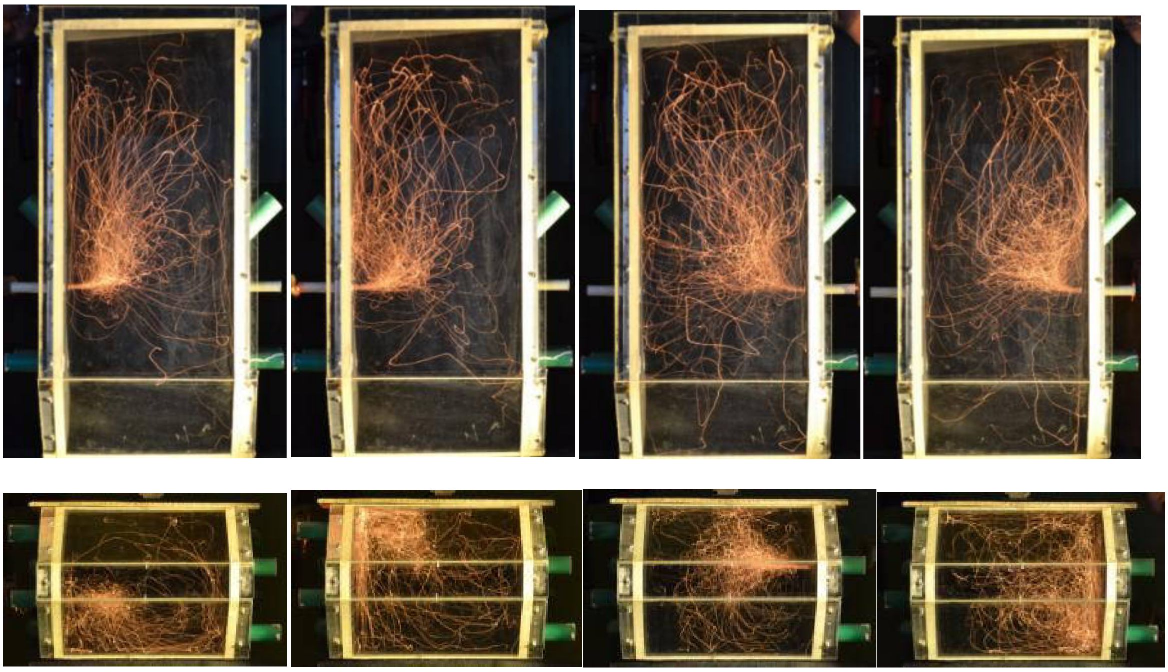
Г1 Г2 Г3 Г4

Fig. 5. **Character of the flow pattern from the burners at spark blowdown**
(view through the front-line wall and boiler throat).



CBB1 CBB2 CBB3 CBB4

Fig. 6. **Character of the flow pattern from the tertiary air nozzles at spark blowdown** (view through the front-line wall and boiler throat).



CTB1 CTB2 CTB3 CTB4

Fig. 7**. Character of the flow pattern from the tertiary air nozzles at spark blowdown** (view through the front-line wall and boiler throat).

As it is known a large share in the total number of nitrogen oxides formed in dry bottom boilers consists of fuel NO_x, that are generated from nitrogen containing fuel components. Their discharge is strongly dependent on the air excess in the fresh burner jets [7] and is reduced with the decreasing oxidant concentration. In the projects [4 and 8] it is noted, that early heating and ignition by the increase of the contact surface of jet fuel with red-hot flue gases also lead to the reduction of the fuel NO_x generation.

Intensive flow around the fresh fuel jet and the presence of the recovering environment on the initial combustion area (warming up, ignition and volatile substances combustion) helps to reduce intensity of fuel NOx formations. In [4] it is noted, that when using less effective mixing burners the significant reduction of NO_X formations can be achieved only if the primary air excess in the fuel-air jet does not exceed the proportion of volatiles from burned coal defined on the fuel working mass. However, lowering the air excess in the fuel-air jet cannot be lower than the values of the corresponding stable coal dust transportation in fuel pipelines.

2.2. Differences in installation diagrams of duct burners and nozzles at the boilers №№2-5

According to the information above and CJSC "CCB Energoremont" projects in Tashtagol production-heating boiler-house in the period from 2009 to 2011 four boilers were successfully reconstructed (№2, 4, 5 and 3 – in chronological order of their reconstruction). There were the boilers of specified type in order to increase reliability, economy and environmental effectiveness of their work [9]. On each reconstructed boiler small changes were put in the layout and construction of the burners and nozzles.

However, the principal features of the implemented staged combustion technology to Kuznetsk coal of G, GR and D grades remained unchanged. These include:

- the use of highly installed and angled down four straight-flow burners, transporting into the furnace the primary air in mixture with coal dust, which is ground in grinding mills;
- secondary air enters the furnace through four secondary blast nozzles; they are located below the burners and they are fuel ignition burners when starting the boiler;
- for turbulence of the tail section of burner flames the dynamic pressure of tertiary air jets is used, arising from four nozzles;
- burners, secondary and tertiary air nozzles are installed by the counter-shifted scheme of vertical-horizontal tangential flames on the furnace side walls.

In Fig.8 key reconstruction plans are shown, in table 1 the main structural features of burners and nozzles are presented.

Table 1. **General construction features of burners and nozzles of the retrofitted boilers**

Boilers №	2	3	4	5
Burner setting mark, m	11,000	9,590 – medium (9,280/9,900)	10,000	10,400
Cross section in embrasure	Ø426x7 mm with horizontal divider	Vertical and horizontal dividers. 4 channels 80x210 mm	Rectangular 450x120°mm	Rectangular 450x150°mm
Angle inclination of burners	45^0	$30^0/40^0$	60^0	60^0
Ignition perimeter (total for furnace), m	6,84	14,512	8,16	8,4
Diameter and number of fuel supply pipelines to burners	Ø219x6 mm, two	Ø193,7x6 mm, two	Ø219x6 mm, two	Ø325x8 mm, one
Burner location	Above CBB on opposite wall	Above CBB on opposite wall	Above CBB	Above CBB
Number of grinding mills on load D_{nom}	2	2	2	1 (two in all)
Diameter and number of fuel pipelines from grinding mill	2, Ø273x6 mm	2, Ø273x6 mm	2, Ø273x6 mm	4, Ø325x8 mm
CBB mark Tilt angle CBB cross section	7,100 Horizontal Ø426x5 mm	7,100 15^0 Ø377x6 mm	7,100 10^0 Ø478x5 mm, inside – Ø377x5°mm	7,100 10^0 Ø478x5 mm, inside – Ø377x5°mm
CTB mark Tilt angle CTB cross section Location	9,500 Horizontal Ø219x7 mm Above CTB	10,000 30^0 Ø159x5 mm Above CTB	10,350 30^0 Ø159x5 mm Opposite to burners	10,750 30^0 Ø159x5 mm Opposite to burners
Minimum load without lightning by fuel oil, % of D_{nom}	30	40	42-45	85…90 % (under the terms of reliable dust transportation to burners)

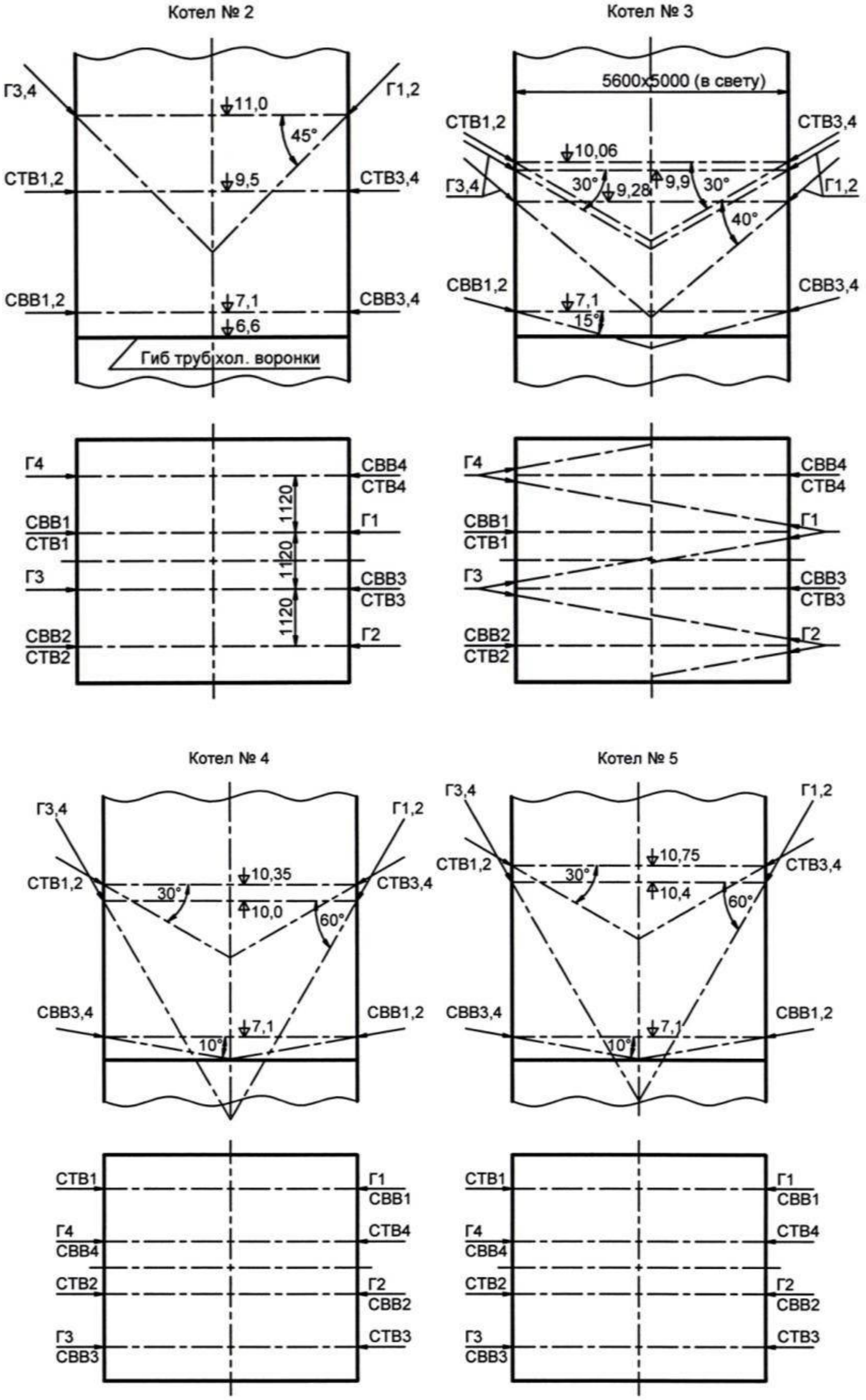


Figure 8**. Installation diagrams of duct burners and nozzles at К-50-14-250 boilers**
Note: Котел - boiler

3. THE MAIN TEST RESULTS OF THE RETROFITTED K-50-14-250 BOILERS

Tests were conducted by joint team of MPEI staff and boiler-house personnel in accordance with the recommendations that are shown in [10] with the use of devices that have passed on-time calibration. At boilers №№4 and 5 adjustment tests were carried out in 2012, at boiler №2 - in 2009, at boiler №3 — in 2013.

The main boiler operation parameters were read from the board devices. Dust-air mixture pressure was evaluated according to the readings of portable U-tube manometers. Moisture and ash content of raw coal, the grinding fineness of coal dust and the combustibles in fly ash were determined in the chemical laboratory of the boiler. UKEK Ltd handed several averaged samples of raw coal, characterizing periods of tests to the Novokuznetsk branch laboratory to determine their characteristics, including the calorific value and content of volatiles.

Measurements of O_2, CO, and NOx concentration in combustion products after the steam superheater, flue gasses and before the smoke exhauster were conducted with the use of calibrated portable device “Testo-342-3”. Thermocouple embedded in this device was used in each experiment to duplicate the temperature measurement in flue gases.

Flare temperature evaluation through the peep holes on the secondary air nozzles and through the front hatches of flame presence in the furnace (in fresh burner jets) was carried out by optical pyrometer with disappearing heating filament “Promin’-KCH1” type.

Adjustment works carried out at K-50-14-250 boiler (№2) [1] revealed positive results of the modernization, during which there were used direct-injection burners, secondary and tertiary air nozzles as well, installed by four at the furnace side walls under the counter-shifted scheme. These results are the following:

- prolonged available maximum load of the boiler increased to 50 t/h, which was limited by air draft deficit before the reconstruction;
- the minimum available boiler load was reduced from 32 to 15...20 m/h during its operation at one grinding mill according to reliable condition of burning Kuznetsk coal of GR-GROK grades without lighting the flam with expensive fuel oil;
- unburned carbon loss reduced by 2.5...3°%, which satisfies the normative values of 2…3°% [11] (depending on the fuel ash content);
- specific emissions of nitrogen oxides in exhaust gases reduced from 800…850 to 460...465 mg/m^3 at D_{nom}, i.e. to the normative level [2].

At the same time, in [1] there were indicated the unresolved problems of modernized boiler operation:

- big cold air leakages into the furnace and convective heating surfaces of the boiler, which reduce reliability and economic efficiency of its operation;
- low tertiary air velocities (at the rated load less than 16...18°m/s), that deteriorates a process of mixing the reagents the in furnace;
- increased gas temperature after the boiler bank and after the boiler compared to their estimated values.

To increase the completeness of coal dust afterburn and for gas temperature reduction at the furnace and boiler outlet, under agreement with the Customer –“Yuzhno-Kuzbasskaya energy company” Ltd., the projects of the second modernization phase of K-50-14-250 (№№4 and 5) boilers, which have been upgraded in 2010 and 2011, include the following changes:

- at the boilers №№4 and 5 the burners were installed at a height of 10,4 and 10,0°m (along the axes of furnace tubes) downward at an angle of 60°; they were made of rectangular cross section with a height in diagonal cut of 900 mm and with a width of 150°mm and 120 mm respectively, while at the boiler №2 they are placed at the level of 11.0 m, inclined downwards at an angle of 45^o, made of tubes of Ø426x7°mm and equipped with dividers, disposed horizontally;
- secondary air nozzles, made of Ø426x5 mm tubes at the boiler №2, are directed horizontally and installed at a mark of 7,1 m in the burner plane on the opposite walls. At the boiler №№4 and 5 secondary air nozzles are installed at a mark of 7,1 m under the burners (on the same walls) and are inclined downwards at 10^o. By that, bodies of secondary air nozzles are made of tubes of Ø478x5 mm and are provided with central channels of Ø377x5 mm with possibility to turn the air off by closing the respective shutters;
- tertiary air nozzles are installed at the mark of 10,75°m (boiler №5) and of 10,35 m (boiler №4), inclined downwards at an angle of 30^o, made of Ø159x5 mm tubes, while at the boiler №2 tertiary air nozzles were installed at a height of 9,5°m, directed horizontally and made of Ø219x7°mm tubes.

During the adjustment works conducted at the retrofitted boilers №№4 and 5 at the bottom of burners there were installed demolition canopies of 550 mm long to avoid slagging of the boiler throat, reducing the angle of inclination of burner bottom walls. Thus their height in an diagonal section was reduced to 600 mm.

Under the initiative of YKEC Ltd., at the boiler №5, and then at the boiler №2 heating surfaces of the second stage of water economizer were increased twice. As a result of these activities, as shown by tests, flue gas temperature was decreased and air draft reserve was created. At the same time the undesirable result was registered - decrease in hot air temperature by 80…85°C.

This has led to a slight increase in the unburnt carbon in fly ash due to lower flare temperature. So, at the boiler №2 the unburnt carbon in fly ash increased to 0,5…1 %, and the minimum available load without lightning the flare by fuel oil increased to 21…23 t/h (from 15…20 t/h, when the hot air temperature was relatively high).

The tests conducted at the modernized boiler №5 showed an increase in its operation reliability and economic efficiency: available boiler load increased to 50…52 t/h, and the flue gas temperature has dropped to 185 ^{o}C. The unburned carbon in fly ash, which substantially reduced compared to the pre-reconstruction period, was slightly more than at the boiler №2, and amounted 4,5…6°% – depending on the quality of coal burnt.

It should be noted that the results of tests conducted at the reconstructed boilers relating to their economic efficiency depend not only on implemented technical solutions designed for burners, and also secondary and tertiary air nozzles. The results of operation of the reconstructed boilers are deteriorating due to some operational factors.

The negative impact of cold air leakages into reconstructed boilers furnaces (to 30…35 %) is cooling the flame and decreasing the prolongation of the coal dust burning period. In a number of cases for the tertiary air velocity increase and unburned carbon reduction in fly ash, it was needed to increase the excess air ratio in the exhaust gases to 2,0 or even more, which leads to raising heat losses with exhaust gases, overconsumption of electricity for draught and blowing and was associated with uncalculated air leakages into the convection shafts of the boilers.

MPEI staff, as well as the duty and repair men of the boiler-house due to mill table depreciation and insufficient pressing of rolls failed to reduce the residue of coal dust on a sieve of 200 mkm below 15…21 % (at adopted acceptable level of 2 %) at one of grinding mills of the boiler°№4 by closing separators valves. As a result, the unburned carbon in fly ash of this boiler in case of two operating mills amounted to 4…6 %. Thus, it decreased to a value of about 1 % only after disabling this grinding mill (including at the fixed minimum boiler load of 24°t/h).

Full closure of shutters before the central channels of secondary air nozzles at the boilers 4 and 5 while maintaining the drying agent flow rate led to a decrease in specific NO_X emissions to 430 mg/m^3 and 370 mg/m^3 respectively at D_{nom}. This indicates that the fuel oxides generation process stretched along the trajectory which is longer than air mixture motion trajectory before the meeting (mixing) point with secondary air.

During the development of technical solutions for the reconstruction of boiler №3 it was considered to be reasonable to design a burner as a four plate channels one (Г) with parameters of 210x80 mm by using horizontal and vertical porthole impellers. By experience of adjusting the burners of the boilers №5 and №4, lower awnings of 220 mm long were welded in the specified channels till the first starting of the reconstructed boiler. By that it was considered that increased velocity of primary air will lead to the suction of furnace exhaust gases into the roots of fuel and air jets with regard to the channel number increase. Thus, the burner of the reconstructed boiler №3 has taken its final form (Fig. 9), and the duct of fuel and fuel mixture before the burners has four vertical splitters (as at other reconstructed boilers) and four glove-like mixers.

Secondary air nozzles (CBB) were made of Ø377x6 mm pipes, i.e. of smaller cross section than at the boiler №2. They were installed at a mark of 7,1 m on the walls opposite to the burners (as at the boiler №2) inclined downwards at an angle of 15^{o}. The mark of tertiary air nozzles (CTB) inclined downwards at an angle of 30^{o} of Ø159x5 mm made 10 m (along the screen axis). As a result, configuration of burners and nozzles of the reconstructed boiler №3 is alike to the one presented in Fig. 10, also. In this Figure the marks of channels of burners and nozzles are given in account of boiler refractory setting.

It should be also noted that during the long period of reconstruction of the boiler №3 under the initiative of UKEK Ltd. a large amount of research activities connected with the boiler convection shaft was conducted: the second stage of feed-water economizer was doubled, two stages of air heater were replaced, sealing and other types of work was done.

Adjustment tests at the modernized boiler №3 were conducted in February and April of 2013. It was considered that closing of secondary air dampers to 20 % at the whole boiler load ratio from 20 to 50 t/h is useful, because in this case the tertiary-air velocity reaches its maximum, especially in view of decreasing cross section of secondary air nozzles (in comparison with the boiler №2 - by 22°%). Herewith in the whole load ratio appears an opportunity of using excess air ratio equal to 1,0 or even higher, including at the nominal boiler load (because of draft reserve).

It should be marked, that at the nominal load for the process flow diagram of the boiler much higher pressure of cold air was recommended (235…240 kgf/m^2), while at other boilers this parameter doesn't go higher than 90-95 kgf/m^2. Air leakages into the gas path of convective shaft of the boiler №3 reduced by 2.5-3 times compared to other boilers, even despite of higher consumption of operational air flow and increased surface of the second stage of water economizer, the air draft reserve is provided. The exhaust tertiary air velocity (in experiments with the position of the secondary air dampers of 20%) made about 45 m/s at the nominal load, instead of 16,1 m/s at the boiler №2 – at the same considered proportion of primary air of 0.45 (with regard to increased cold air leakages into the mills).

Fig. 11 shows the experimental data of operation of the reconstructed boiler №3 depending on the load in the range of 20 ... 50 m/h in optimal experiments when the secondary air dampers are open by 20%.

On the basis of data obtained during testing the boiler №3 (Fig. 12), the experimental dependence of combustibles in fly ash vs the operational excess air in the furnace is created. Its assessment is made in accordance with [11], based on measurements of the leakages of cold air in the area: furnace - horizontal shaft (0.35 at the nominal load).

One can see that with decrease in the arranged excess air from 1.45 to 0.9, combustibles in the boiler №3 gradually decrease from 2 to 1,4°%. At the critical value of α_{arr}=0,885 a sharp increase in $\Gamma_{\text{ун}}$ to 9.0 or even more can be found.

At the modernized boiler №3 in the operational load range, the unburnt carbon is 5 ... 6 times less than the standard value [11]. It should be noted that low values of unburnt carbon occur at the reduced temperature of hot air, including at the minimum boiler load of 20 t/h, when the temperature according to the test was about 250°C.

According to the recommendations [11]: the less the boiler capacity, the more the unburnt carbon. In case D=50 t/h, it is 2 ... 3%, at D = 25 t/h it makes about 5%. At the modernized boiler №3 at an average load of 20,3°t/h the average value of unburnt carbon in four experiments is 0.3%. Thus, it could be assumed that the reconstruction of the boiler №3 resulted in significant reduction of unburnt carbon compared to the standard parameters [11].

Explanation of these low values of unburnt carbon at the boiler №3 at this stage of the study can be only presumed. It is possible that the arrangement of nozzles and burners in accordance with Fig. 10, in conjunction with the fundamental design of burners according to Fig. 9 provided not only pre-ignition of coal dust, but also increased intensification of its afterburning. As a result, this optimization process of coal dust afterburn occurs with significantly higher intensity.

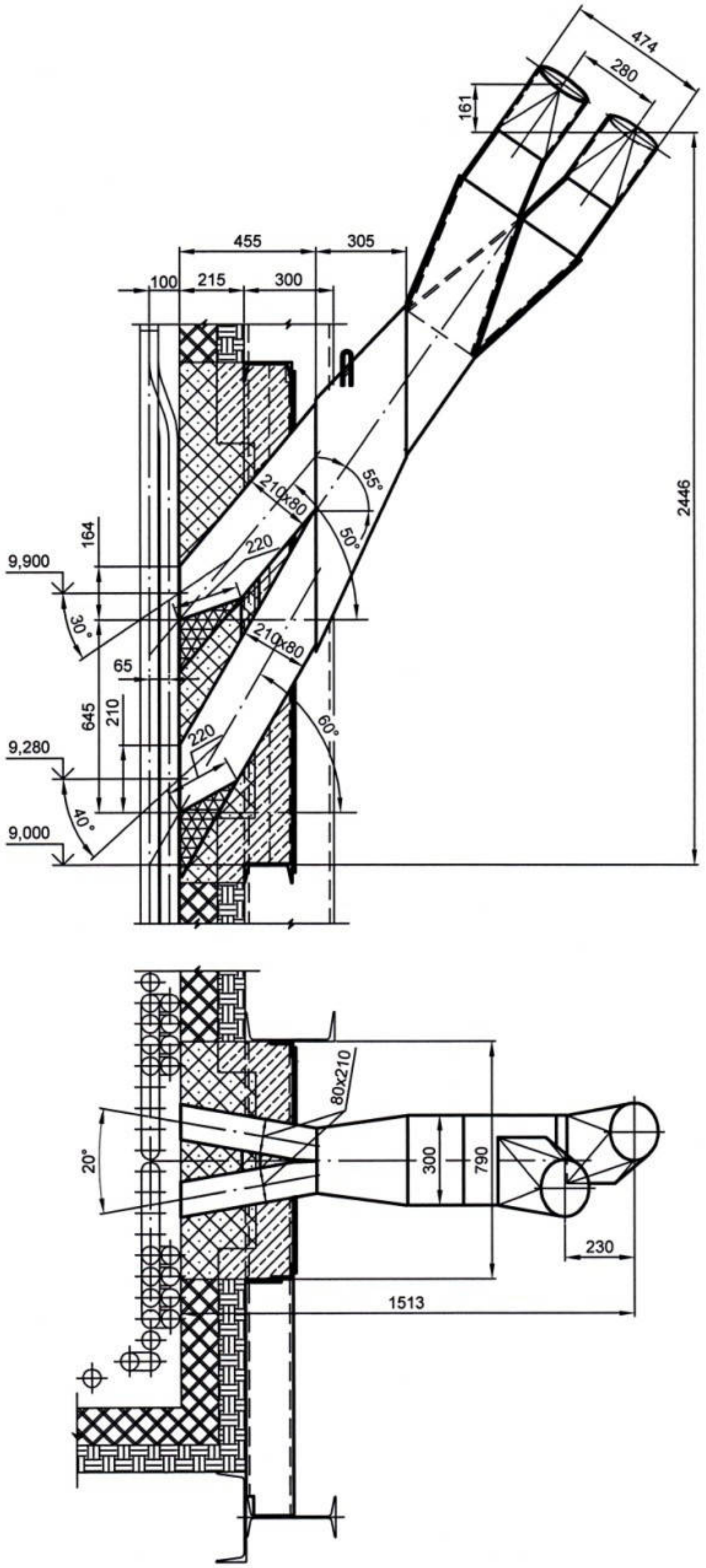


Fig. 9**. Principal design of straight-flow burner of the reconstructed boiler №3 after installing lower awnings.**

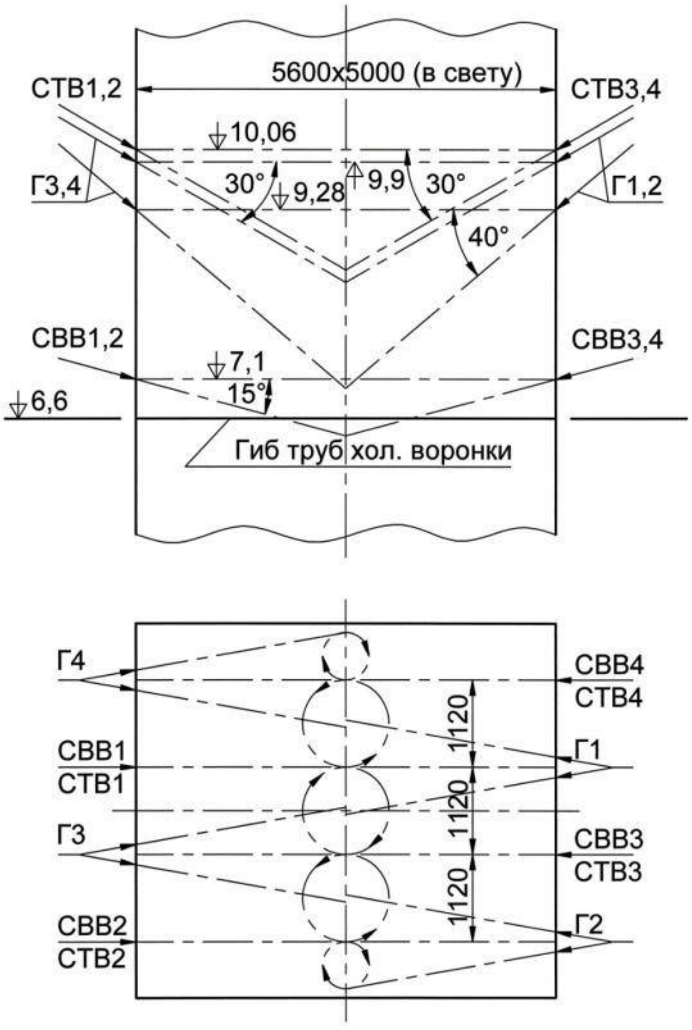


Fig. 10. **Key plan of straight-flow burners and nozzles of the reconstructed boiler №3.**

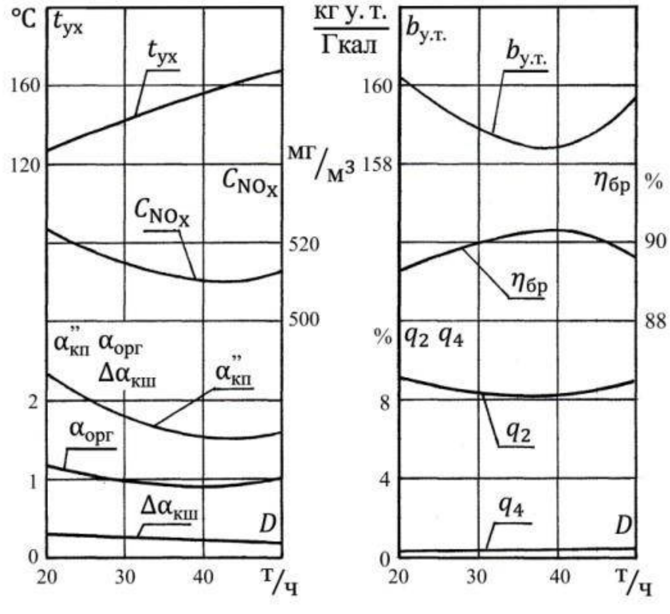


Fig. 11**. Experimental data of the work process of boiler №3 depending on load (*D*).**
Note: Г – Burner, СВВ – Secondary air nozzle

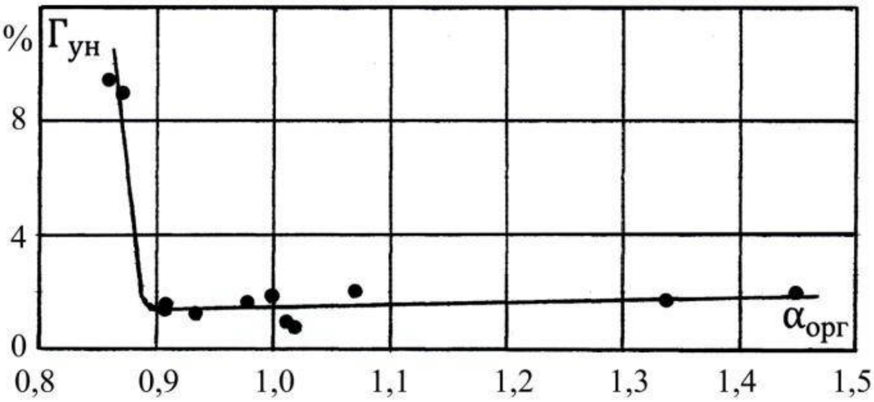


Fig. 12**. Combustibles in fly ash ($Г_{ун}$) of the boiler №3 vs the operational air surplus in the furnace ($α_{орг}$)**

Concerning the flame aerodynamics one can say the following. According to the inferior view (Fig. 10) in the furnace a system of three large horizontal vortices and two side small ones is formed. Combustion products in any two adjacent vortices rotate in opposite directions. This supports, firstly, a relatively large swirl in vortices, secondly, a stable position of the core flame and, thirdly, a sliding movement of the hot burner jets relatively to the front and back furnace walls. One can also see that the inflamed dust and air jets, for example, of the right two channels of the burner 1 (G1) and right two channels of the burner 4 (T4) fall into the back large vortex, mix there with the tertiary air and facilitate the downtake movement of combustion products in this whirlwind. Therefore, in the low plane of the furnace, downtake movement of the burner occurs, at least at the level of 7 ... 9 m. Then, the combustion products are mixed with secondary air, forming vertical vortices under the roots of dust and air jets, burning them.

Combustion products containing more completely burnt coal dust, in the recycling process are pushed out by more "fresh" portions into interjet space of burners and tertiary air nozzles coming up from the area of active burning mainly along the side walls of the furnace.

A major role in providing low unburnt carbon belongs to burner jets and tertiary air jets that are on their upward movement to combustion products and eject them, i.e. create an internal recirculation of combustion products. Let us compare the ejecting effect of these jets approximated by the parameter P·ρ·W2, where P is an ejection perimeter at the burner (nozzle) outlet in the cross-section perpendicular to the flow, ρ is a density of the flow medium, W - exhaust velocity. An approximate comparative evaluation of this parameter for burners and tertiary air nozzles at the reconstructed boilers №№2 and 3 is given in Table 2.

Thus, at the modernized boiler №3 ejection processes of combustion products by jet roots occur with intensity 20.3 times higher than at the not modernized boilers, and with intensity 1.74 times higher than at the modernized boiler №2. Presumably, this is one of the reasons of the mentioned significant reduction of the unburnt carbon at the boiler №3, especially at the low load.

It should be also considered that at the retrofitted boiler №2 in the horizontal projection of the furnace a hit of oppositely directed tertiary air jets with burner jets occurs, while at the modernized boiler №3 jet roots of the burners eject the tail masses of tertiary air jets (see the lower projection, Fig.10). Thus, at the boiler №3 increase in ejection of flue gases by roots of burner jets and air-fuel mixture ignition is provided by the layout scheme of burners and nozzles, i.e. flame aerodynamics.

Measurements of the flame temperature at the load close to the nominal, performed using an optical pyrometer with a disappearing filament by looking through the visor of the secondary air nozzles (7.1 m mark), showed that is made at an average of 1255° C. At the same time, the flame temperature in the ignition zone, measured through two front flaps (8.7 m mark), was significantly higher and made 1470°C.

Specific emissions of nitrogen oxides at higher loads of the boiler №3 are within 480 ... 535 mg/m^3. The boiler №2 in accordance with [1] meets the norm of 470 mg/m^3. While the adjustment setup of the boiler №3 a possibility to reduce specific emissions of NOx to a normative level by reducing the proportion of primary air (from 0.45 to 0.4 ... 0.35) was found. However, by that reliability of operation of coal-pulverization systems decreased due to increase in the probability of their blockage; at the same time it is known that the operating personnel prefer to work with a margin of the equipment safety.

To improve the environmental safety of the boiler №3 it is advisable to switch to a gas (gas and air) coal dust drying, as in this case, specific NO_x emissions will be lower due to reduced primary air share. Increase in the tertiary air velocity leads to double raising of its ejecting capacity by jets of combustion products. As a result, the intensity of mixing of the reactants increases, which compensates the factor of lowering the temperature in the furnace due to the external gas recirculation. Besides at the retrofitted boiler №3 according to the tests and analysis of the estimated data (Fig. 11, Table 2), a factor of increasing the tertiary air flow velocity is predominant in its influence on unburnt carbon.

Table 2. **Assessment of the mentioned parameter for burners and tertiary air nozzles at the reconstructed boilers #2 and #3**

Parameter, unit of measurement	Boiler K-50-14-250 in basic design	Boiler №2 after retrofitting with double increased surface of water economizer second stage	Boiler №3 after retrofitting with double increased surface of water economizer second stage
Number of burners, pcs Type	4, whirl-type	4, straight-flow [1]	4 burners with 4 channels, straight-flow (Fig. 9, 10)
Nozzles, pcs	none	4 secondary and 4 tertiary air nozzles [1]	4 secondary and 4 tertiary air nozzles (Fig. 10)
Continuous available maximum draft load, t/h	31…35	48-50	50
Minimal available load without oil lighting, (number of mills in operation)	31…32, (2 mills)	21…23, (1 mill)	18…21, (1 mill)
Combustibles in fly ash, %, (load, t/h)	10…12, (31…35)	7…9, (48…50)	0,8…2,1, (20…50)
Boiler gross efficiency, %, (load, t/h)	86,0-86,5, (31…35)	88,6…89,0, (48…50)	88,7-90,5, (20…50)
Arranged excess air factor at the nominal load	0,9	0,9	1,0
Primary air ratio	0,45	0,45	0,45
Air-fuel mixture density (ρ_1), kg/m^3	1,357	1,357	1,357
Air-fuel velocity (W_1), м/с, without moisture vapor	10,7	24,88	29
Perimeter of fuel gas ejection by air-fuel jets from the burner periphery (Π_1), m	- (secondary air ejection)	6,84	7,406
Product: $\Pi_1 \rho_1 W_1^2$, kg/s^2	- (secondary air ejection)	5746	8452
Hot air density ($\rho_{ha} = \rho_2 = \rho_3$), kg/m^3	0,529	0,529	0,612
Secondary air velocity at the nominal load (W_2), m/s	11,2	16,1	20
Ejection perimeter of fuel gases by secondary air (P_2), m	$\pi \cdot 0,7 \cdot 4 = 8,796$	5,228	4,587
Product: $P_2 \rho_2 W_2^2$, kg/s^2	584	717	1123
Tertiary air velocity (W_3), m/s	-	16,1	44,9
Perimeter of fuel gas ejection by tertiary air jets (P_3), m	-	2,576	1,872
Product: $P_3 \rho_3 W_3^2$, kg/s^2	-	353	2310
Sum: $P_1 \rho_1 W_1^2 + P_2 \rho_2 W_2^2 + P_3 \rho_3 W_3^2$, kg/s^2	584	6816	11885
Reference fuel consumption for one Gcal produced, kg ref.f./Gcal (load, t/h)	166,3…165,3 (31…35)	161,4…160,7 (48…50)	160,2…158,4…159,7 (20…40…50)

4. THE PROPOSED SCHEME FOR THE RECONSTRUCTION OF FUEL COMBUSTION IN THE BOILER №1

While developing the new layout, the decision was taken to abandon the implementation of tertiary air nozzles at the boiler №1 for the following reasons:

- furnace of the boiler №1 is by 1.4 m lower than other boilers of the Tashtagol boiler-house. Therefore, the available length of the flame path for mixing of its tail section with the tertiary air is not sufficient, as was proved by the highest gas temperature after the boiler beam at this boiler;
- in [1] it is noted, that due to low capacity of K-50-14-250 boiler and a lack of the unit for the mechanized bottom ash removal with hydraulic lock, it’s impossible to reduce the air inflow at the section “furnace – superheater” to values less than 0.3 ... 0.35. In this connection the arranged air flow is restricted, and the velocities of secondary and tertiary air are too low to provide an intensive mixing of the reactants;
- an attempt to increase the tertiary air velocity at the boilers #4 and #5 due to complications of secondary air nozzles (use of interruptible central channels) is not approved by the operating personnel, as at one operating mill in case of flame failure or outage of coal, there is no time to open the respective gates, when it is necessary to carry out a quick light of the flame by fuel oil.

Fig. 13 shows the layout scheme of burners and nozzles, which will be introduced at the boiler №1. The main design parameters of the layout scheme are shown in Table 3.

When selecting the calculated excess air at the outlet of the burners and nozzles there were considered the results of tests performed at boilers №№2, 4 and 5, reconstructed under MPEI recommendations [9]. It was found that when burning quality coal of D and GR grades (with moderate moisture and ash content) the excess air after the superheater can be reduced to 1.15 ... 1.2, even at the level of air leakages to the furnace and steam superheater of 0.35 In this case, a certain amount of air sucked through the lower part of the furnace (for example, through the ashpit) was timely involved in the combustion process, thanks to the efficient aerodynamic of the combustion process. As a result, the content of combustibles in the fly ash is not more than the specified level (14%), unless there is a dramatic deterioration of coal burnt.

Table 3. **General design parameters of burners and nozzles, which are to be used at the boiler №1**

Parameter name	Dimension.	Burner	Nozzle
Quantity	Pcs	4	4
Height	m	10,0	7,1
Downward angle	deg	40 (average by height)	15
Calculated air excess: $\alpha_{pp} = 1{,}2$; $\Delta\alpha_{т+pp} = 0{,}35$	–	0,4	0,45
Total air consumption	m^3/s	35,2	10,32
Environment temperature	^oC	60	356
Exit cross-section view	–	Vertically enlarged rectangle (750 mm high, 60 mm wide)	Ellipse (pipe of 341 mm in bore in angular cut)
Total perpendicular cross-section	m	0,138	0,365
Outlet velocity	m/s	35,2	28,3

The recommended option of the principle burner design is shown in Fig. 14. At the bottom of the projection can be seen that two dust lines of Ø194 × 7 mm (one from the divider belonging to the mill A, and another - of divider of the mill B) are connected via a tee. Outlet section of this tee is: height - 300 mm, width - 150 mm, as can be seen from the upper projection of Fig. 14.

Then the burner body is set that tapers to a width of 60 mm and a height of 750 mm in the outlet section in its angular cut. By height the body is divided by the downward sloping partition into two compartments with the same orifice. The partition continuation forms an angle of 40° relative to the horizontal plane drawn to the screen layout of pipes under the burner at around 10 m. There are eight screen pipes in the pipe routing for one burner.

Fig. 15 shows a perspective view of the model for the study of furnace aerodynamics of the boiler №1. The model is made in scale 1: 19.5.

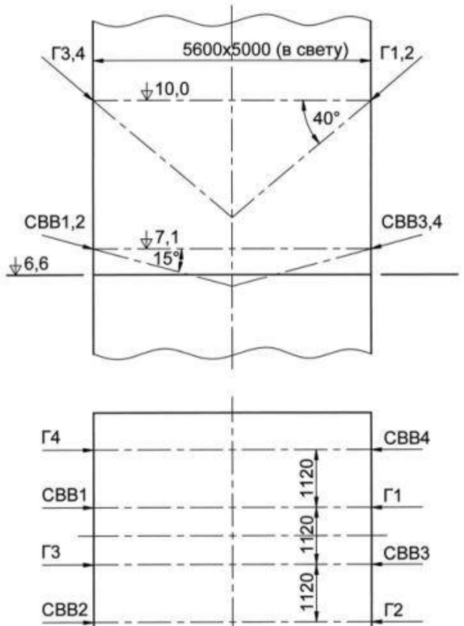


Fig. 13**. Straight-flow burner layout.**
Г – burner, СВВ – secondary air nozzle

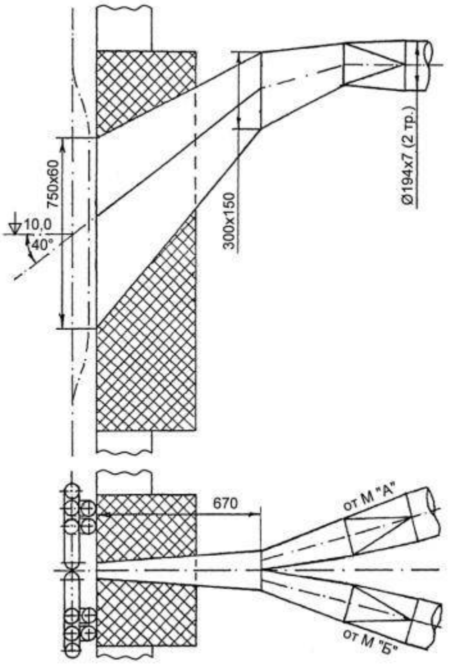


Fig. 14**. Key layout of coal dust straight-flow burner at the boiler №1.**

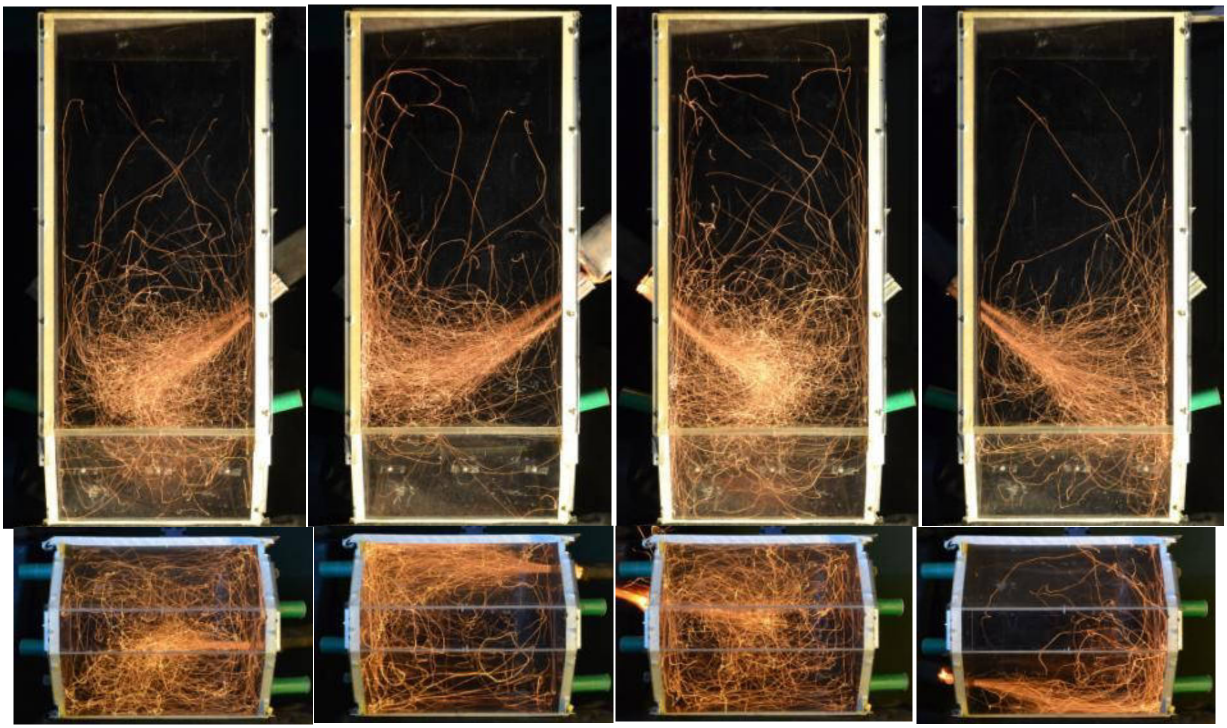
Fig. 15. **General view of the test plant for studying furnace aerodynamic of the boiler №1.**

Fig. 16 shows a character of movement of burner jets in the volume of the model with a view from the front wall and boiler throat at spark blowdown of channels. One can see that burner jets first move as slow-widening flows. In the central part of the model expansion of burner jets increases, especially after interacting with jets of opposite-shifted burners and nozzles installed in the same vertical planes with the corresponding burners. It occurs about 1 m higher than the level of junction of vertical screens with boiler throat slopes. After this interaction tail volumes of two central burner jets (Г1 and Г3, Fig. 16) come to the center of the boiler throat and almost uniformly fill a left and a right sides of the model on the lifting sections of the furnace. At the same time, side jet burners (Г2 and Г4, Fig. 16) mostly fill a volume of the model along their initial movement that is explained by a braking motion of neighboring counterjets from one side.

A character of moving the burner jets with a view through the boiler throat slopes (Fig. 16) proves the conclusion about the uniform and safe from the point of view of possible screen slagging, burner aerodynamics.

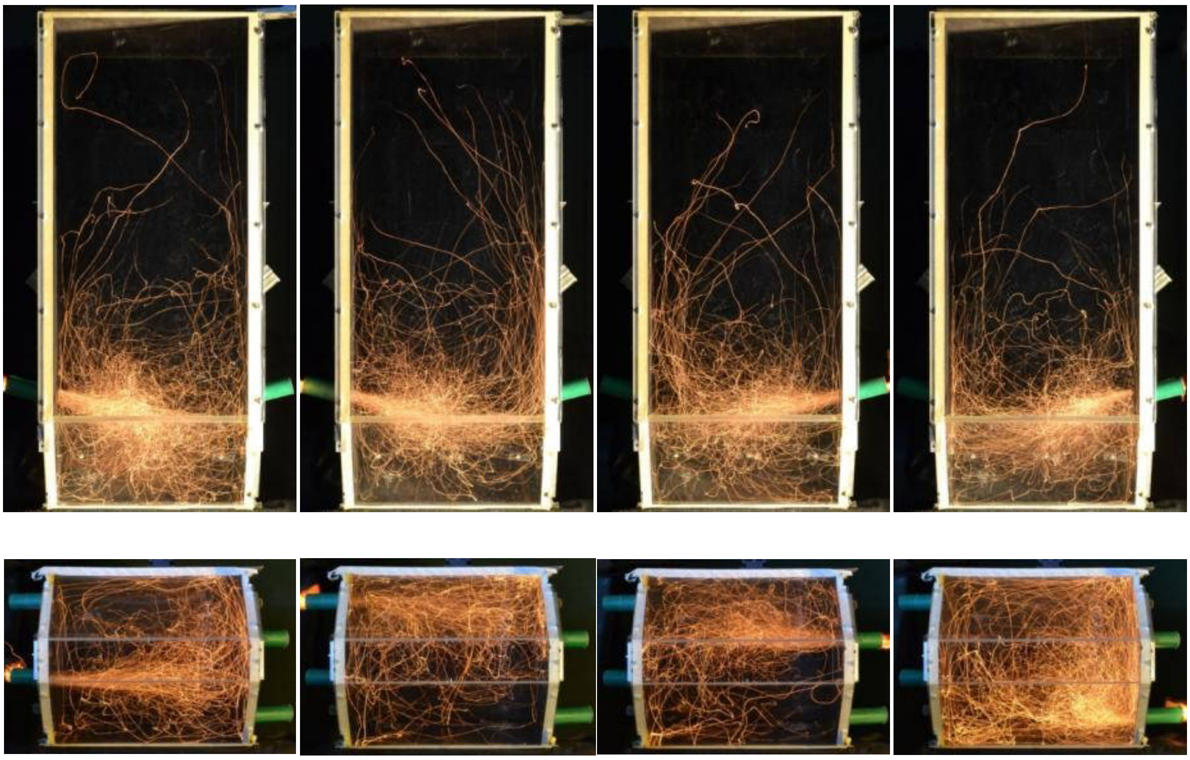
In Fig. 17 a character of jet motion flowing out to the model volume through the nozzles is shown (a view from the front wall and through the boiler throat slopes). One can see a good filling of the model transverse cross sections.

Local volumes of fuel and air jets rise into the upper part of the model along the same trajectories in a fairly uniform proportion. This demonstrates the reliability of mixing of the primary (mixed with the coal dust) and the secondary air.



Г1 Г2 Г3 Г4

Fig. 16. **Nature of burner jets motion during spark blowdown (front wall and boiler throat view).**



CBB1 CBB2 CBB3 CBB4

Fig. 17**. Nature of secondary air jets motion during spark blowdown during spark blowdown (front wall view and boiler throat view)**

CONCLUSIONS

1. Considering the developed recommendations four steam K-50-14-250 boilers have been modernized at Tashtagol boiler-house. For those boilers it was developed and implemented the technology of fuel burning in straight-bushy flame in the system of vertical and horizontal tangential flames at straight injection of coal dust. As a result of testing the retrofitted boilers №№2-5, a high efficiency of the developed technology was found out:

- after reconstruction maneuverability range of the boilers greatly expanded (minimum load made 30 ... 40% of the nominal value;
- continuous maximum available steam load increased to a nominal (due to decrease in pollution of heating surfaces of convective shafts while increasing the efficiency of combustion);
- boiler efficiency increased by 2.5 ... 4.5% (mainly due to unburnt carbon decrease by 2.5 ... 3% and reduction of excess air in flue gases);
- NO_x concentration in flue gases reduced more than by 400 mg/m^3;
- high stability of pulverized coal combustion was achieved and, consequently, fuel oil consumption for its lightning was reduced;
- as a result of reconstruction, the boiler №3 showed very low value of unburnt carbon, which is unique for dry bottom boilers (less than 0.5% in the whole operating load range). It’s associated with the optimal configuration of burners and nozzles of secondary and tertiary air at this boiler.

2. Combustion technology in vertical and horizontal tangential flames is realized through the installation on side walls of the furnace using the opposite-shifted scheme of four downwardly sloping straight-flow burners, four nozzles of secondary and four nozzles of tertiary air. At the reconstructed boilers №№2-5, the burners have different forms of outlet sections, marks of location and downward angles. Secondary air nozzles are installed at all boilers below the burners, have different downward angles and have cylindrical form. When starting the boilers, they play the role of oil-fired burners. Tertiary air nozzles installed at these boilers are also cylindrical and are differ by marks of their location and downward angles. Differences in layout and design of furnace and burner units (straight-flow burners and nozzles) were due to the search for optimal solutions to improve reliability, environmental safety and efficiency of the reconstructed boilers.

3. Aerodynamics of burner jets at all the retrofitted boilers is characterized by three tangential horizontal flames projected on a horizontal section of the furnace. By that the adjacent flames are rotating in opposite directions which contributes to a better mixing of flue gases and temperature equalizing in the furnace volume. In vertical planes of burner setting their jets and the jets of secondary and tertiary air are directed tangentially to the vertical conventional circles, forming the vertical flare formations (mixing zones).

4. Aerodynamic features of the flame, designed with the help of research on physical models, provide:

- dispersal of the core flame by width, depth and height of the furnace;
- high efficiency of reactants mixing due to the nature of counter motion of adjacent jets, as well as the products of combustion in adjacent vertical vortex formations;
- intensive forced flue gas supply to roots of burner jets, i.e. pre-ignition of coal dust;

- protection of side furnace screens from the dynamic pressure of the burner flame located at opposite walls due to aerodynamic impact from the side of fresh jets of response burners and nozzles;
- use for combustion of a considerable amount of cold air leaked into lower parts of the furnaces into fresh jets of burners and nozzles due to ejection (according to evaluations made during commissioning tests, the amount of cold air leakage at the section: furnace- boiler beam at K-50-14-250 boilers was 30 ... 35%)

5. The best performance in terms of specific emissions of nitrogen oxides at the rated load show the modernized boilers№№4 and 5 (NO_x = 370 and 430 mg/m^3, correspondingly) in modes with full gate closure in front of the central channels of secondary air nozzles. Reduction of specific NO_x concentration in case of closed gates makes 75 ... 140 mg/m^3 and refers to lowering the generation of fuel nitrogen oxides, since according to the flame pyrometry in the ignition zone the temperatures are by 200 ... 220°C higher than in the central zone of the furnace (in traditional furnaces with swirl burners inverse temperature difference can be found). At the same time, gas temperature in ignition zone does not exceed 1450 ... 1470°C, i.e. it's somewhat below the level characteristic for the beginning of thermal NO_x formation. The observed reduction of fuel NO_x generation with a decrease in oxygen concentration in a zone of junction of burner jets with secondary air jets shows that the process of fuel NO_x formation is stretched in time and by trajectory of the fuel jet. At the first of the retrofitted boilers – the boiler №2 specific emissions of nitrogen oxides were reduced from 800 - 850 to 460 ... 465 mg/m^3.
6. During conducting thermal tests at the modernized boilers №№2-5, optimal modes of fuel combustion were identified and parameter tables of boiler operation were developed.
7. Testing of the reconstructed boiler №1 under developed recommendations will be conducted in November-December 2014.

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