P a r t 4

COMPLEX TECHNOLOGIES OF ENVIRONMENTAL POLLUTION FROM THERMAL POWER PLANTS

4.3. Combustion of solid fuel

4.3.2. Influence of arrangement of the staged combustion of kuznetsky coals on specific NOx emissions and operational reliability of slag-tap boilers TP-87

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ABSTRACT

Analyses of three stages of TP-87 boiler reconstruction at Zapadno-Sibirskaya CHPP are resulted. The purposes of reconstruction consisted in decrease in NOx emissions and increase in reliability and profitability of the boiler operation at combustion of kuznetsky coal of GR and GROK ranks. Technical solutions for stag-tap boilers of TP-87 type on increase in operational reliability and decrease in specific NOx emissions to the standard level are offered.

TP-87 boiler of the JSC "Zapadno-Sibirskaya CHPP" was reconstructed in 2005 under development of Boiler Plants and Ecology in Power Engineering Department of MPEI and the JSC "CKB Energoremont" [1] in order to decrease in nitrogen oxides emissions. The layout scheme of burners and nozzles, and also supply air lines in longitudinal section of the furnace is presented in fig. 1.

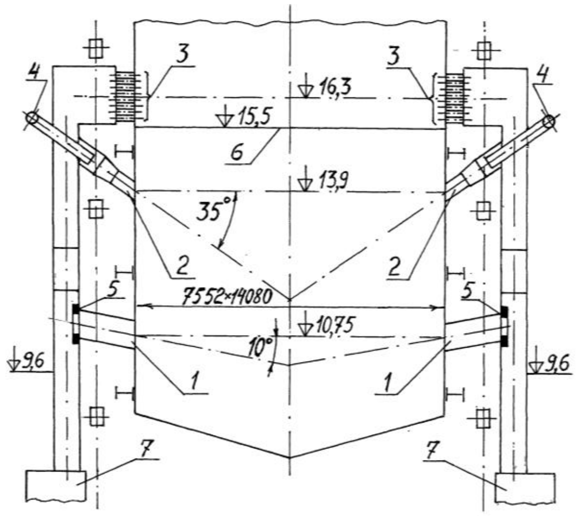

Fig. 1. A layout scheme of burners and nozzles, and supply air lines: *1* – dist-oil burner of 720×7 mm; *2* – combined nozzle of 377×6 mm; *3* – unit of eight pipes of 133×6 mm, incoming to the tertiary air nozzle; *4* – discharge dust pipeline of 325×6 мм; *5* – limiting washer of 470 mm; *6* – level of screen lining; *7* – hot air collector.

Twelve direct-flow burners, due to turn at an angle of 8,5° in relation to the normal, in a horizontal projection of the furnace, form a system of anti-displaced jets (ADJ), which provides a steady position of the flame in the furnace center and its raised turbulence. The inclination of burners downwards by 10° provides the reliable washing of the furnace bottom (by results of blowing out the isothermal model of the furnace, fig. 2) and fast burning out of the separated dust on a film of liquid slag.

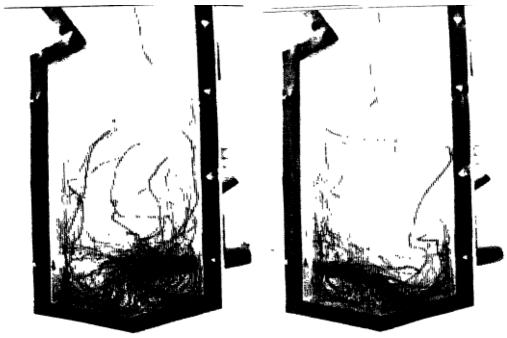

Fig. 2. Behavior of tertiary air jets: *a* — nozzle № 4; *b* — nozzle № 9.

Twelve combined nozzles of 365 mm are intended for feeding of waste agent from dust preparation system and a small share of secondary air to the furnace. They have a significant inclination downwards (35°) to prevent from lifting of the primary flame in central zone of the furnace and for reliable burning out of the fine dust. In the horizontal projection of the furnace, they form ADJ system due to their turn by 8,5° in relation to the normal, but to the opposite side in relation to burners. The estimated excess air at the combined nozzle outlet (in case of two dust preparation systems in operation), was 0,42. Model investigations showed that these features of configuration of the combined nozzles provide good mixing of jets with the primary flame (fig. 3) and partially compensate asymmetry of aerodynamics of burner jets.

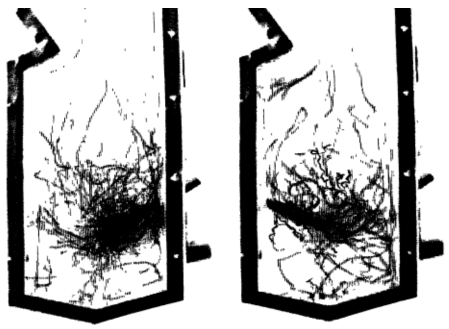

Fig. 3. Behavior of jets of the combined nozzles: *a* — nozzles №4; *b* — nozzles №9.

Nozzles of tertiary air (12 pieces) are installed in vertical planes of burner setting and combined nozzles, and are directed horizontally. Each nozzle represents itself a unit of eight pipes of 133×6 mm, which are directed next nearest at an angle of 8,5° to the normal to different sides in a horizontal projection. Such configuration of nozzles provides a steady flow of jets. Besides, the total initial ejection perimeter of all jets, following from one nozzle, is 2,84 times larger than the same parameter for the round jet, following from the nozzle of equivalent section, and 2,37 larger than in case of rectangular jet, following from equivalent nozzle, in which wall thicknesses are in the relation of 2:1. By character of jet flowing (fig. 4) it is possible to draw a conclusion that in the central zone of the furnace there is an intensive process of reagent mixing.

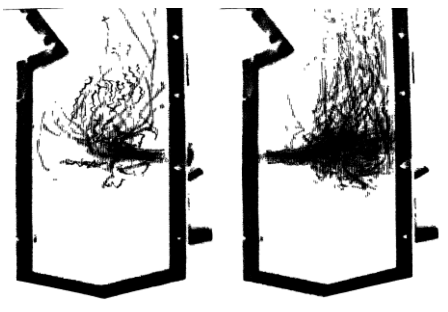

Fig.4. Behavior of tertiary air jets:
a — nozzles № 4; *b* — nozzles № 9.

Configuration of the design dust-oil burner is presented in fig. 5.

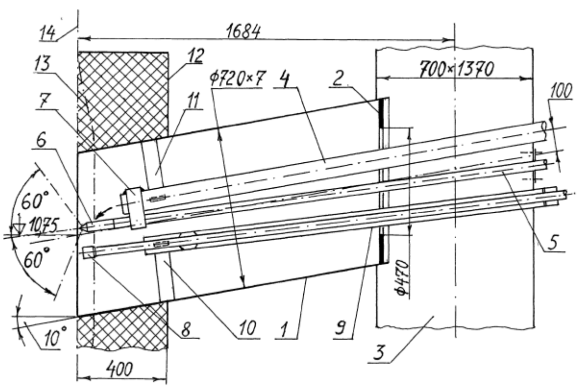

Fig. 5. Dust-oil direct-flow burner: *1* — body; *2* — restrictive washer; *3* — air box; *4* — pipe of high-concentration dust (HCD) of 89×6 mm; *5* — pipe of the compressed air of 42×5 mm; *6* — pneumatic jet spreading orifice; *7* — yoke; *8* — head of steam-mechanic sprayer; *9* — sprayer pipe; *10* — plates of sprayer pipe fixing; *11* — plates of HCD pipe fixing; *12* — throat box; *13* — screen pipes parted inside the throat; *14* — axis of the screen pipes.

Coal dust is supplied to the furnace, using HCD technology. HCD spreading is provided by the compressed air at pressure of P = 0,4 … 0,45 kgf/sm^2 flowing out at the velocity of about 190 m/s from twelve holes of 4 mm diameter, located in staggered order at the conic side surface of the spreading nozzle *6*. The spreading angle is 120°. At the inlet in the burner case of 720×7 mm in diameter, the restricting washer of 470 mm in diameter is set.

At the majority of tests, conducted together with the regime group from ZSCHPP after three phases of boiler reconstruction, for spreading HCD, conic spreaders were used. They fastened to HCD pipes *4*. The spreader bases of 180 mm in diameter were set on cuts of burners, and the tops – at a distance of about 70 mm from the side of HCD pipes, thus there were no pipes of the compressed air 5.

During the tests at the reconstructed boiler in October-November, 2005, there were gained good results relating to reliable output of liquid slag, level of specific NOx emissions, temperature of flue gases and the unburnt carbon (fig. 6).

As presented in graphs, at operational excess air after the steam superheater (SSH) α_{SSH} = 1,25, specific NOx emissions made about 560 at the standard level of 570 mg/m^3 instead of 1150 … 1200 mg/m^3 before reconstruction. The unburnt carbon value was before 0,55 % that meets the similar indicator in case of operation of unreconstructed boilers TP-87 at stoichiometric burning. The relative temperature of flue gases made 134°C that is by 5 … 7°C less, than in case of unreconstructed boilers. Indicators presented in fig. 6, insignificantly depend on boiler loading and excess air α_{SSH} after SSH in a range of 1,1 … 1,32. In the majority of tests at the raised boiler loadings, the gross boiler efficiency made about 92 %. During the tests, kuznetsky coal of GR and GROK ranks were combusted with the following range of characteristics: Q_n^r=4378…5847 ccal/kg, W^r=8,75…17,03 %, A^r=11,7…20,66 %, V^r=40,8…42,4 %, N^r=2,4…2,5 %. Fineness of coal dust grinding R_{90} corresponded to standard requirements and made 14 … 15 %.

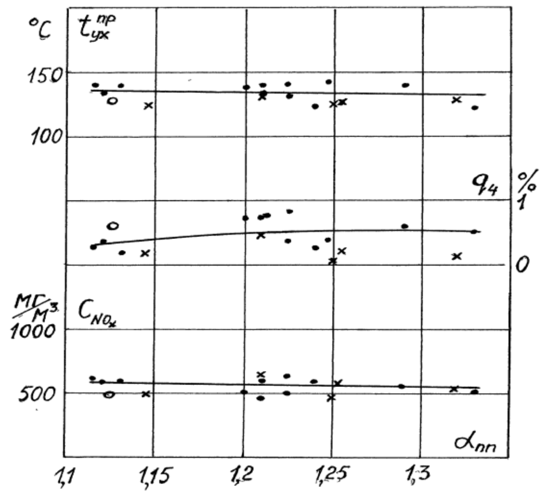

Fig. 6. Specific NOx emissions, unburnt carbon and equivalent temperature of flue gases versus excess air after the steam superheater at the modified boiler TP-87: • — в two crushers are in operation; × — one crusher in operation; o — two crushers are stopped; мг/м^3=mg/m^3; $\alpha_{пп}$=α_{SSH}; $t_{ух}$=$t_{flue\ gas}$

However, after the first reconstruction of the boiler, off-design increase in gas temperature after SSH, which occurred more intensively, than at stoichiometric combustion in unreconstructed boilers TP-87, with overclamping in the furnace, was fixed. Analyzing results of the tests it has been established that it occurred due to pollution of SSH and screens of the furnace above the studied zones. The mentioned processes at the staged combustion in the boiler №9 are the result of insufficient height of the flame after-burning zone and disuse of means for operational cleaning of screens of the furnace and SSH.

In summer, 2006 the boiler №9 was stopped for conducting the second phase of reconstruction. The main objective of that consisted in increase in height of the flame after-burning zone due to decrease in level of the boiler bottom and marks of setting the burners and nozzles by 2,5 m. By results of zone calculations of the furnace executed in MPEI, gas temperature at the level of aerodynamic lug should decrease by 80 … 90°C and make about 1160°C. Thus, it would be lower than ash melting temperature for coal of GROK rank (≈ 1200°C).

There were also made decisions on inclination of tertiary blasting nozzles by 30° for braking and turbulence of the burning down flame, and also decisions on complete recovery of means of steam blowing of screens at medium and top sections of the furnace. Besides, the following has been recognized expedient: reduction of a share of tertiary air due to liquidation of restrictive washers before burners, separation of a box of air intake to burners and nozzles of tertiary blasting and possibility of regulating air consumption by regime means.

Analyzing the test results and data on boiler operation after the second phase of its reconstruction, gained in the winter, 2006 - 2007, it has been established that at combustion of GR and GROK coal, intensity of SSH pollution hasn't almost changed. It was visually fixed, despite of increase in furnace height by 2,5 m in a zone of the flame after-burning, inclination downwards of tertiary air nozzles and reduction of its share.

Measurements of air inflows in the furnace and horizontal flue duct have shown, that their share make about 0,3 in recalculation on the rated boiler load. In this connection the arranged air supply in the furnace was reduced due to draft lack. Most likely, SSH pollution occurred owing to dust after-burning in it, because of a lack of the arranged air in the furnace, owing to decompression of the furnace and horizontal flue duct. At the same time, economic indicators of boiler operation were higher: gross efficiency made about 93 %, and loss on ignition — 1 … 2 %,

From the point of view of MPEI experts, during the boiler reconstruction it was necessary to condense the boiler and recover the means of steam blowing of screens in its middle and top sections for decrease in intensity of SSH pollution. Besides, it was offered to carry out regular cleaning of the non-screened inclined wall of horizontal flue duct by gas-impulse or pneumomechanical methods. Directly at this site of the flue duct occurred depositing of the burning down particles of coal and ash, resulting in avalanche-like pollution of the bottom part of the horizontal flue duct and bottom bends of SSH pipes.

However the management of ZSCHPP, despite of objections of MPEI experts, under proposal of the JSC “Yuzhteplo-complekt”, IAC “Kuzbassenergo” and the regime group from Tom-Usinskaya SDPP, participating in adjustment of the boiler, has made a decision to change the staged combustion technology due to reduction of angulation of the combined nozzles downwards from 35 to 15°. Besides, the decision to simplify a design of tertiary air nozzles was accepted, having executed them in the form of rectangular channels, and lower HCD pipes to the burner axes. The last action could intensify separation of the large unburnt dust at the furnace bottom.

As a result of tests of the boiler after the third phase of reconstruction at combustion of coals of GR and GROK ranks, essential decrease in reliability of liquid slag output from the boiler gates and intensity growth of burner slagging have been revealed. Thus, the main objective of changing the combustion technology, which consists in decrease in gas temperature at the furnace outlet and after SSH, has not been reached.

In our opinion, the main reason of decrease in reliability of wet slag removal and the raised burner slagging after the third phase of the boiler reconstruction, is an adverse change of the flame aerodynamics in bottom and middle furnace sections, owing to premature lifting of a part of the primary flame in the central zone of the furnace. Due to that, intensity of washing of slag, flowing down to the furnace bottom and the unburnt dust precipitated on slag, by high-temperature combustion products with excess oxygen, has decreased. Resulting from that the precipitated dust particles had no time for burning down before their complete immersion in flowing down liquid slag layer and instead of an additional warming up of the liquid slag layer, as it had happened before reconstruction, its viscosity raised due to increase in content of carbon-mineral mass in slag. Liquid slag, flowing down from up-burner sections of front and back screens of the furnace became more viscous, and its beadings at the outlet burner sections were difficult to remove. Before the third phase of reconstruction of the boiler, slag jets were mobile and thin. At their beadings at burner embrasures under influence of burner jets, they bulged towards the furnace and mashed down. After the third phase of reconstruction, watch personnel had to remove slag beadings manually two times a tour.

As a result of the third phase of the boiler reconstruction, reliability of its work was lowered, but high economic indicators were saved and specific NOx emissions were a little bit lowered. In table the specified inflows (taking into account inflows of cold air into the furnace and horizontal flue duct), parameters of operation of burners and nozzles, concerning the periods after all phases of boiler reconstruction, and also the basic indicators of boiler operation as a whole, are presented.

It is necessary to note inconsistent character of some data from the table. For example, there is a qualitative discrepancy of pyrometric temperature levels of the flame before screens and operational gas temperature after SSH and after the 2nd stage of water economizer after the third phase of boiler reconstruction in comparison with these indicators after its previous phases. Gas temperatures, obtained with use of operational devices, are more representative (considering influence of life-time of boiler operation, measurements in several tests). The lowest gas temperature after SSH (645°C) and after the 2nd sage of water economizer (490°C) is fixed at a rated load after the second phase of boiler reconstruction. The highest levels of these temperatures occurred after the third phase of reconstruction (665 and 500°C accordingly). Thus, it is necessary to consider that air inflows into the furnace and horizontal flue duct were the least after the third phase ($\Delta\alpha_{f,hfd} = 0,1$) and the highest after the second phase ($\Delta\alpha_{f,hfd} = 0,3$). At the same time regular blowing of screens of middle and top sections of the furnace began to be conducted since the third phase.

Table. Estimated aerodynamic parameters at the burner inlet and actual indices of operation of the reconstructed boiler Tp-87

Name of the estimated parameter and boiler operation indicator	Reconstruction phase			
	I	II	III	IV (recommended)
Burner characteristic	Fig. 5.Restrictive washer of 470 mm in diameter. Conic HCD sprayer of 180 mm, HCD pipe located by 100 mm higher than the burner axis	Fig. 5. Without the restrictive washer. Conic HCD sprayer of 180 mm, HCD pipe located by 100 mm higher than the burner axis	Fig. 5. Without the restrictive washer. Conic HCD sprayer of 180 mm, HCD pipe located along the burner axis	Fig. 7. Flat channel 500x100 mm. Under the channel the nozzle of secondary air is located
Total flow section of burners in the bottleneck/at the cut, m^2	1,932/4,695	4,9/4,9	4,9/4,9	0,58/0,6
Total cross section for hot air passage through the combined nozzles, m^2	0,589	1,022	1,022	0,589
Total throat of nozzles of tertiary air; features of the nozzle configuration, m^2	1,103; 8 horizontal pipes of 121 mm in diameter, angle left-right next nearest at an angle of 8,5° from the normal	1,103; 8 pipes of 121 mm in diameter inclined down at an angle of 30°, inclination in the horizontal plan from the normal: 0°- two pipes, 45°-left-right next nearest – six pipes	0,926; square channel, inclined down at angle of 15°, the channel is 386 mm high 200 mm wide	1,103; 8 pipes of 121 mm in diameter, inclined down at an angle of 30°, inclination in the horizontal plan from the normal: 0°-two pipes, 45°-left-right next nearest - six pipes
Initial perimeter of ejection by jets at the outlet of tertiary air nozzles (P_{ter})/degree of overlapping by jets of horizontal furnace cross section, m	36,5/small	39,5/high	14,1/small	39,5/high
Excess hot air factor at the furnace inlet at α_{ssh} = 1,25, $\alpha_{dis.}$= 0,3 / ($\Delta\alpha_{f,hfd}$)	0,75/(0,2)	0,65/(0,3)	0,85/(0.1)	0,85/(0,1)
Excess air factor at the outlet of burners/combined nozzles/tertiary air nozzlesa (2 crushers in operation)	0,4/0,422/0,228	0,453/0,395/0,102	0,608/0,427/0,115	0,118/0,42/0,225/at the outlet of tertiary air nozzles 0,387
Air velocity at the outlet of burners (W_{bur})/ tertiary air nozzles (W_{ter}), m/s	17,1/41,5	18,55/18,55	24,9/24,9	28,2/40,95/at the outlet of secondary air nozzles 21,7
Parameter $E_{ter} = P_{ter} \cdot W_{ter}^2$, proportional to ejection of combustion products by tertiary blasting jets, m^3/s^2	62862	13592	8742	66238
Load, t/h	320	315	370	
Results of the flame pyrometry, °C: in fresh jets of frontal burners, the same, but for back burners, before screens, right/left	1590/1600 1610/1590 1310/1310	1580/1585 1550/1580 1285/1250	1430/1485 1525/1520 1275/1260	
Minimum boiler load with steady liquid slag output, t/h	210	240	300	200
Behavior of liquid slag beadings on the burners, type removal	Uncontrolled caving	Uncontrolled caving or easy to remove, manually once a shift	Difficult to remove, manually twice a shift	Uncontrolled caving
Loss on ignition, %	1…3	1…2	1…2	0,5…1,5
Specific NO_x emissions in the range ($\alpha_{ssh} \cdot D_{blow}$), $mg/m^3/t/h$	540…570 (360…550)	610…640 (370…550)	440…550 (400…550)	430…500 (350...550)
Gas temperature after steam superheater/after the 2nd stage of the water economizer at D_{nom}, °C	660/495	645/490	665/500	не более 640/490
Use of regular steam blowing of screens above the ignition belt	no	no	foreseen	foreseen

Low excess air factor and primary air velocity after the first phase of the boiler reconstruction at high values of these parameters at the tertiary air nozzles outlet attract attention. It was possible to ensure this, thanks to restrictive washers of 470 mm in diameter, set before the burners. During this period the minimum boiler load under condition of steady liquid slag output made 210 t/h, and beadings of liquid slag on embrasures of burners didn't reduce reliability of their work. As it is specified above, they bulged towards the furnace and subjected to uncontrolled caving in the form of fine icicles of slag hardening in the air flow. Decrease in viscosity of the beading film of liquid slag was promoted by a high degree of washing by high-temperature gases of front and back screens in up-burner zone up to nozzles of tertiary blasting. It was connected with high dynamic pressure on a primary flame of jets of the combined nozzles, inclined downwards at an angle of 35°, and with the raised ejection ability of tertiary air jets since parameter E_{ter} made 62862 m^3/s^2 (table).

On the contrary, after the third phase of reconstruction owing to declination of the combined nozzles downwards to 15° and depression of parameter E_{ter} to 8742 m^3/s^2, degree of washing the hot gases of up-burner zone of front and back screens became less. It resulted in growth of viscosity of liquid slag beading on embrasures of burners that sharply lowered reliability of their work. Coming out of a part of the primary flame upwards in the central zone of the furnace led to depression of gas temperature at the gate zone. As a result of cumulative influence of the specified factors, the minimum boiler load under condition of reliable output of liquid slag increased to 300 t/h. Apparently, this was also promoted by rising of primary air factor to 0,61 from 0,4 after the first phase of reconstruction.

It attracts attention the fact that after the second phase of the boiler reconstruction, despite of the lowered level of ejection ability of tertiary air jets (in comparison with the period after the first phase) (E_{tr} = 13592 m^3/s^2 to 62862 m^3/s^2), and also the raised air inflows in the furnace and horizontal flue duct ($\Delta\alpha_{f,hfd}$ = 0,3 that prolonged after-burning of the coal dust), the gas temperature after the steam superheater was the least (645°C). It was promoted by an optimum design of tertiary air nozzles, consisting in their declination by 30° at the large degree of overlapping the horizontal cross section of the furnace by fresh jets (table). As a result, a skip of furnace gases upwards, containing the burning down coal dust, without contact with tertiary air, has been almost excluded.

A design of tertiary air nozzles and combined nozzles with their declination at an angle of 30°, promoted that after the second phase of the boiler reconstruction, specific NOx emissions appeared the greatest and made 610 … 640 mg/m^3 due to intensification of hashing and some increase in formation of thermal NOx. After the third phase of the boiler reconstruction, when the mixing processes of the flame with tertiary air, and, especially, with air following from the combined nozzles, became less intensive, specific NOx emissions appeared the least and made 440 … 550 mg/m^3.

It is necessary to dwell on the issue of reliability of HCD spray at the burner outlet. The most reliable sprayer, preventing from burning, is the pneumatic jet sprayer 6 (fig. 5) as its heat reception side surface is small, with the side wall, cooled by the compressed air from inside. The least reliable were sprayers of Tom-Usinskaya SDPP design, because of rather large size (426 mm in diameter). Sprayers of ZSCHPP design of 180 mm in diameter, considered at estimation of aerodynamic parameters of burners after three phases of reconstruction, and used at the most part of tests, had the average reliability indices preventing from burning.

On the basis of analysis of the gained results, in case of slag-tap boiler operation, it is recommended to use the slot-hole direct-flow burners set under the scheme of high-velocity jets. These burners represent a combination of slot-hole burners and secondary air nozzles located under them. Their design with regard to TP-87 boilers (fig. 7) is recommended by MPEI for introduction at dry bottom boilers [2]. And the forecast is given, that these burners will provide a low level of fuel NOx formation, since excess air at the burner outlet is less, than a share of volatiles, counted up on the working weight of coal.

Unlike the process of volatiles ignition in burners of the reconstructed TP-87 boiler, especially after the 3rd phase of the boiler reconstruction (with the raised α_{prim} = 0,61), in the offered burner design, ignition and burning of volatiles will start earlier. It will be promoted by three factors: the raised initial ejection perimeter (1,0 to 0,57 m for one burner), a compulsory supply of highly-temperature furnace gases to roots of burner jets and low level of primary air excess. Early burning of volatiles will occur in the regenerative medium (α_{prim} = 0,118 at an average share of volatiles v^r = 0,263). Therefore, according to [2] it is expected that generation of fuel NOx will be reduced by 30 … 40 %, and the total formation nitrogen oxides together with thermal NOx, despite of a little increase in the last, will make less than 500 mg/m^3.

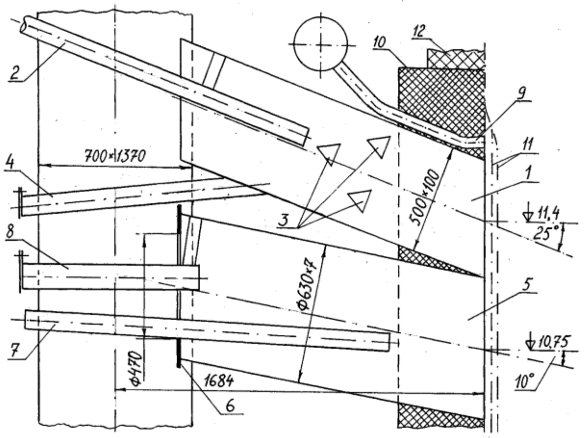

Fig. 7. A principal configuration of the recommended burner and secondary air nozzles for slag-tap boilers of TP-87 type: *1* – slot-hole coal dust burner; *2* – HCD pipe; *3* – corner sprayers; *4* – pipe for observing the burner work; *5* – secondary air nozzle; *6* – restrictive washer; *7* – sprayer pipe; *8* – pipe for observing the nozzle embrasure; *9* – cold air pipe for cooling the slag in the top section of the screen pipes distribution above the coal dust burner; *10* – a box of the joint burner and nozzle embrasure; *11* – distribution of the screen pipes for the joint embrasure; *12* – furnace lining.

After reliable and early ignition of the coal dust (including the dust with the lowered volatile content on working mass, for example, intermediate product), there will be a penetration of the lighted up flat burner jets into the hot secondary air flows. It will be promoted by a difference of velocities, lag effect of particles and that the angle of burner slope (25°) is more than the angle of slope of secondary air nozzles (10 °).

It is expected that owing to early ignition of all mass of the coal dust and its subsequent guaranteed hashing with secondary air, the minimum boiler load under condition of reliable liquid slag output, should be no more than 200 t/h, even at coal deterioration. After the third phase of the boiler reconstruction at decrease in the volatile content and increase in ash content of coal, the specified loading increased to the value of more than 300 t/h because of ignition delay.

In the last column of the table estimated parameters and expected operational indicators of the boiler TP-87 after the fourth phase of its reconstruction under MPEI recommendation and introduction of the optimum combustion technology, considering fig. 7, are resulted. When estimating parameters and the expected indicators for the newly reconstructed slag-tap boilers, the following was accepted:

- the boiler bottom doesn't go down, since by experience, gained after the previous phases of reconstruction, working conditions of slag removal units worsen (insufficient slag cooling in cylindrical channels after the gates because of their small height, the constrained conditions for arrangement of hydroshutters, suction schemes, etc.);
- the design complete set of blowing devices of the furnace screens in medium and top sections of the furnace should be operated;

- it is necessary to mount 10 devices for pneumomechanical cleaning of the unscreened inclined wall of the horizontal flue duct (fig. 8).
- air inflows in the furnace and horizontal flue duct make to 0,1 (a flue gas path of the boiler should be condensed);
- the combined nozzles are executed like after the first phase of the boiler reconstruction, and 4 dividers of discharge air are set by 2 at the furnace sides on vertical sections that (unlike the boiler after the second and third phases of reconstruction) provides uniformity of discharge air flow rate through 12 combined nozzles;
- tertiary air nozzles are declined by 30^o and consist of 8 pipes of 133×6 mm, and angulations of separate pipes in the horizontal projection are executed similarly to solutions on the second phase of the boiler reconstruction, since it provides the improved contact of the burning down flame with tertiary air;
- vertical hot air lines to nozzles of tertiary blasting (fig. 1), are executed of the increased cross section without regulating bodies for saving the greatest possible dynamic pressure of jets, thus, there should be aerodynamically identical performance of the front and back air lines, that was not possible to realize after the second phase of the boiler reconstruction;
- before nozzles of secondary air of 630×7 mm restrictive washers of 470 mm are set.

Arrangement of the staged combustion, recommended by MPEI, is preferable, that follows from the expected indicators of reliability, profitability and ecological compatibility of the reconstructed TP-87 boiler (table).

CONCLUSIONS

1. Complex efficiency of three phases of reconstruction of slag-tap TP-87 boiler, realized for NOx emissions reduction into atmosphere, was analyzed.
2. Specific NOx emissions were lowered to the standard level (570 mg/m^3) and even more, as a result of realization of the first and third phases of reconstruction with increase in profitability of the boiler operation at combustion of kuznetsky coal of GR rank.
3. After the second phase of the boiler reconstruction, specific NOx emissions made 640 mg/m^3.
4. The minimum boiler load under condition of reliable liquid slag output made 210, 240 and 300 t/h accordingly after the 1st, 2nd and 3rd phases of its reconstruction. Growth of the minimum boiler load occurred owing to deterioration of aerodynamics of the flame because of erroneous reduction of inclination of the combined nozzles downwards from 35° to 15° at the third phase of reconstruction.
5. The raised degree of polluting the steam superheater at the staged combustion (especially after the 1st phase of the boiler reconstruction) is explained by the raised air inflows in the furnace and horizontal flue duct, absence of the steam blowing of screens above the ignition belt and means of operational cleaning of the unscreened inclined wall of the horizontal flue duct.
6. At combustion of kuznetsky coal of GR and GROK ranks in slag-tap TP-87 boilers, MPEI recommends to introduce reconstruction of burner devices (fig. 7 and 8) with the following estimated efficiency:
   - specific NOx emissions - less than 500 mg/m^3;
   – loss on ignition - 1 … 2 %;
   - the minimum boiler load D_{min} — less than 200 t/h under condition of reliable liquid slag output;
   - the maximum boiler load D_{max} = 420 t/h under condition of absence of intensive pollution of steam superheater surfaces;
   - possibility of reliable, high-efficiency and environmentally sound operation of TP-87 boilers at combustion of kuznetsky coals of the worsened quality and intermediate product.

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