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STEAM BOILERS, POWER FUEL, BURNERS, AND BOILER AUXILIARY EQUIPMENT

Experience of Implementation of In-furnace Methods of Decreasing NO_x in E-320-13.8-560GM Boilers: Problems and Ways for Their Solution

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Abstract—During natural gas combustion, the content of nitrogen oxides in combustion products is approximately 450 mg/m^3 in many E-320-13.8-560GM boilers in service, which is more than 3.5 times higher than the established maximum NO_x concentrations in flue gases for such boilers. Estimates according to the existing techniques have shown that gas combustion on the basis of in-furnace techniques (the feeding of combustion products to burners together with air in the volume of 15% and two-stage combustion with 20% air feeding through the nozzles upstream of the burners) enables one to decrease NO_x emissions to the level of concentrations of less than 100 mg/m^3, which is lower than the maximum allowable values. However, the application of any of the proposed measures with respect to a boiler makes its operation under normal load significantly difficult, since the thermal capacity of the superheater is higher in both cases, which leads to an increase in the temperature of superheated steam above the maximum allowable temperature. On the basis of the developed adapted boiler model, which was created using the Boiler Designer software, we performed numerical studies to determine the required boiler reconstruction volume; the implementation of this reconstruction will provide reliable boiler operation at all working loads and ensure the normative values of NO_x emissions. According to the results of thermal calculations, it was proposed to reduce the surface of the cold stage of the superheater circuit and increase the size of the economizer. It is noted that the implementation of environmental protection measures usually decreases the boiler efficiency. At the same time, it has been established that the technical and economic performance of the E-320-13.8-560GM boiler does not decrease owing to an increase in the economizer surface and a decrease in air inflows and overflows in regenerative air heaters and remains at the same level if the air inflow volume decreases from the available 30 to 20%. The fundamental solutions that were used for the E-320-13.8-560GM boiler to decrease NO_x emissions can also be used for other BKZ gas-and-oil-fired boilers.

Keywords: gas-and-oil-fired boiler, nitrogen oxides, flue gas recirculation, staged combustion, thermal calculations

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The E-320-13.8-560GM (BKZ-320) boiler is designed for superheated steam generation at TPPs with cross-links. This is a natural-circulation, single-drum, vertical water-tube, nongasproof boiler with a double-pass configuration designed for balanced draft operation. The Sibenergomash Production Association has manufactured 24 of these boilers with different modifications and almost the same thermal circuit and they generally differ in the design of separate heating surfaces as well as by the type of burners and their configuration techniques and the presence or absence of control combustion zones in the furnace. One of these boilers is the object of this research and is described below (Fig. 1).

DESCRIPTION

The boiler furnace is open and prismatic. The plan section of the furnace is 5.440 × 12.096 m. Six vortex oil-gas burners are configured on the frontal wall of the furnace in two lines at elevations 6300 and 9300 mm. The vertical walls and floor of the furnace are closed by evaporating walls from tubes with a size of 60 × 5.5 mm (12X1MF steel) from below and tubes with a size of 60 × 6 mm (St20 steel) from above. Above the tubes, the floor is laid with firebrick. The rear wall in the upper part forms an aerodynamic nose required for better gas flow over semiradiation platens. The roof is shielded with superheat tubes with a size of 38 × 4 mm (St20 steel).

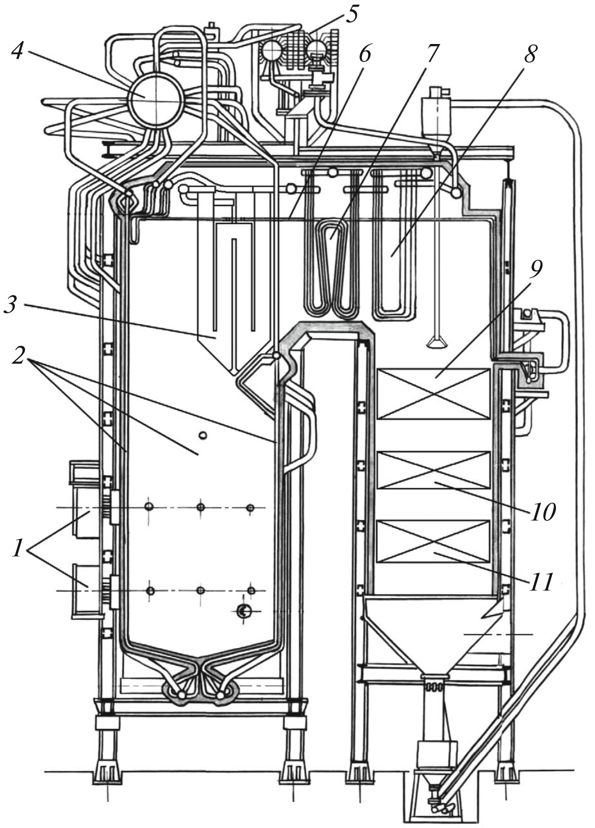

Fig. 1. BKZ-320 boiler. (*1*) Burners; (*2*) evaporating furnace walls; (*3*) semiradiation platens (Ps); (*4*) drum; (*5*) self-condensate units (SCUs); (*6*) roof superheater; (*7*) prefinal stages of the convective steam superheater (CS2); (*8*) last stages of the convective steam superheater (CS3); (*9*) cold convective stage of the steam superheater (CS1); (*10*) upper bank of the economizer (EC2); (*11*) lower bank of the economizer (EC1).

Feed water first enters the self-condensate unit (SCU) and then passes through the economizers EC1 and EC2 in two flows. Both of them are staggered and countercurrent and are made of tubes with a size of 32 × 3.5 mm (St20 steel). The water then enters the drum with an external diameter of 1600 mm and a wall thickness of 100 mm.

The smaller portion of saturated steam from the drum enters the SCU and the greater portion enters the boiler superheater, which is designed in the form of two symmetrical independent controlled flows. The steam enters the first pass of the roof superheater. It includes 149 roof tubes, along which steam moves directly to the turning chamber (TC), where the roof tubes reach and go along the rear wall of the TC. From this place, the steam enters the first stage of the convective superheater CS1; this stage is staggered and countercurrent and is made of tubes with a size of 32 × 4 mm. This stage is followed by the first condensate spray and the steam then moves towards the frontal furnace wall through 150 boundary tubes of the TC rear wall and roof.

The working fluid then enters the semiradiation platens that are arranged in a series-parallel circuit and are made of 12KhMF steel and consist of 12 edge platens (P_{edge}) and 20 middle platens (P_{middle}). This is followed by the second condensate spray into the gap between the P_{edge} and P_{middle}. The edge platens are U-shaped and countercurrent, each containing 25 tubes with a size of 32 × 4 mm in the belt. The middle platens are W-shaped and direct-flow, each containing 12 tubes with a size of 32 × 4 mm in the belt. Downstream of the platens, the steam enters the prefinal stage of the superheater CS2.

This stage is direct-flow and is also arranged in a series-parallel circuit: 74 edge coils (CS2_{edge}) go first and 74 middle coils ($\text{CS2}_{\text{middle}}$) then follow. Both the edge and middle coils have a tunnel tube configuration; each coil has three tubes, two loops, and 12 tube banks in the direction of gas flow. Almost all the tubes are made of 12KhMF steel; however, CS2_{edge} uses a tube with a size of 32 × 4 mm and $\text{CS2}_{\text{middle}}$ has a tube with a size of 32 × 5 mm. Downstream of the CS2, the third self-condensate spray is made and the steam then enters the CS3.

The final stage of CS3 is tunnel and direct-flow and is also arranged in a series-parallel circuit. The working fluid first passes through 74 edge coils and then 74 middle coils. The coils are identical: each coil has four tubes, one loop, and eight tube banks in the direction of gas flow; the size of the tubes is 32 × 5 mm, and the material is 12KhMF. However, the first four tube banks are configured with a longitudinal pitch of 50 mm and the latter four banks are configured with a pitch of 100 mm. Downstream of CS3, the steam moves to a consumer.

CHOICE OF TECHNOLOGIES OF REDUCING NO_x EMISSIONS IN BKZ-320 BOILERS

Most of the BKZ-320 boilers in service have operated for over 30 years; however, they are in satisfactory condition owing to the reasonable operation process and timely repair works. The main problem of their further operation is that nitrogen oxide emissions exceed the allowable values regulated by [1].

The tests of E-320-13.8-560GM boilers at Ufa TPP-2 showed that the content of nitrogen oxides in exhaust gases that is reduced to the excess air coefficient, $\alpha = 1.4$, is approximately 450 mg/m^3 during operation at loads similar to rated ones. This is more than 3.5 times higher than the established normative NO_x concentrations in flue gases for boilers of this type. It is possible to reduce NO_x emissions in gas-and-oil-fired boilers by taking technological in-furnace measures, i.e., on the basis of the use of low-emission burners, staged combustion measures, and flue gas recirculation to burners.

It should be noted that the replacement of burners by new, low-emission ones is not always economically sound, especially for old boilers. Therefore, it is reasonable to use combustion product recirculation, which is not provided for in the boiler under consideration, and two-stage combustion to reduce NO_x emissions in BKZ-320 boilers that have been in operation for 30 years or more, given the good condition of available burner units. Both these methods are widely used and quite efficient [2]. Estimates according to the technique in [3] showed that, during gas combustion, the feeding of combustion products into burners together with air in the volume of 15% and two-stage combustion with 20% air feeding through nozzles upstream the burners should reduce emissions to 100 mg/m^3.

Unfortunately, the implementation of environmental measures may influence the thermal operation of a boiler. In the case under consideration, the implementation of any of the proposed measures makes the combustion of natural gas impossible at the rated load, since the thermal capacity of the steam superheater will be higher in both cases, albeit due to different causes. In the first case, the gas flowrate will increase in the duct path section covered by recirculation. As a result, the rates of product combustion, as well as convection coefficients and heat-transfer coefficients, will increase in the steam superheater stages. In the second case, the air temperature will increase at the furnace outlet, which will lead to a growth in temperature difference in the platens and convective stages. In addition, according to the data of [4], two-stage combustion is characterized by a trend towards a growth in the excess-air coefficient at the outlet of the furnace. Therefore, the gas flowrate through the gas boiler passes and the intensity of the convective heat transfer process also increase here, albeit to a lesser extent.

Another negative aspect is that it is difficult to maintain the superheating temperature at the design level ($t_{\text{superheat}}$ = 560°C) during the operation with rated steam capacity (D = 320 t/h), since this requires operating control and intervention by an engine operator. This is due to the deficit of spray condensate. The boiler is provided with four SCUs, each having the capacity of 12.5 t/h. However, since they are arranged upstream of the economizer along the water, their total output reaches 65 t/h. However, in practice, this is sufficient only for steady operation with D = 300–310 t/h.

Therefore, it is possible to implement the above-mentioned environmental protection measures only after some reconstruction of boilers. To assess the volume of reconstruction, one should perform boiler thermal calculations both under the existing operational conditions and in recirculation and/or staged combustion operating regimes.

CALCULATION STUDIES ON BOILER OPERATION

An adapted boiler model was developed for performing calculation studies. The Boiler Designer [5] software and the technique of [6] were used during its creation and the performance of thermal calculations. The results of the performed tests and, partially, the process flow diagram (PFD) for natural gas combustion were used as a basis for the development of the model.

The main results of the performed calculations are given in Table 1. Variant 1 corresponds to gas combustion at a load of 100% in the existing boiler and adequately reflects the features of its operation. In particular, one can note that the water temperature upstream of the economizer $t'_{\text{ec1}} = 270°\text{C}$, due to a high condensate flowrate for spray, which is 40°C higher than the feed water temperature. As a result, the temperature difference decreases in the economizer and the exhaust gas temperature ϑ_{ex} is significantly higher than that in the case of SCU water installation into the gap between the EC1 and EC2, which is characteristic of the overwhelming majority of operating BKZ-320 boilers.

During oil-fired boiler calculations, the values of the coefficients of contamination and thermal effectiveness were adjusted in the input file for the Boiler Designer software according to [6]. The oxygen concentration in the control section, the $t_{\text{superheat}}$ value and the air temperature downstream of the air heaters, t''_{ah} = 70°C were assumed according to the recommendations of the PFD. As could be expected, during oil burning at rated load, the total condensate flowrate for spray, $D_{\text{spr}\Sigma}$ is significantly lower than that during gas combustion, and is approximately 8.4 t/h (variant 2). The exhaust gas temperature ϑ_{ex} = 157°C is significantly higher than that for variant 1 due to air heating in the air heater, which leads to a decrease in the boiler efficiency.

The simulation of two-stage combustion operating regimes took into account that the temperature at the furnace outlet, ϑ''_{f}, and the excess-air coefficient in the control section, α_{control}, should increase. Given the accumulated experience of implementation of this measure, it was assumed that α_{control} should correspond to the volume concentration of oxygen in dry gases, $O_2 \approx 2\%$, and ϑ''_{f} should increase by 50°C. ϑ''_{f} was increased on the basis of the relevant change in the parameter that takes into account the pattern of temperature distribution over the furnace height [6]. If we simulate the two-stage combustion regime for operation at a load of 100% under the conditions of the limited condensate flowrate for spray, $D_{\text{spr}\Sigma}$ = 65 t/h, the superheated steam temperature will be 613°C, which is unacceptable according to the operating conditions for the superheater and equipment upstream of the boiler. However, if we remove the limitation on the SCU capacity, we can achieve the value $t_{\text{superheat}}$ = 560°C at $D_{\text{spr}\Sigma} \approx$ 95 t/h (variant 3). In addition, the water temperature upstream of the economizer increases to 289°C and the ϑ_{ex} increases to 152°C in this case. For this reason and due to the increase in α_{ex}, the boiler efficiency decreases by 0.3% compared to variant 1.

Table 1. Main results of calculations for the BKZ-320 boiler

Parameter	Variant									
	1	2	3	4	5	6	7	8	9	10
Fuel	Gas	Fuel oil	Gas	Gas	Gas	Gas	Gas	Fuel oil	Fuel oil	Gas
Two-stage combustion	NA	NA	Available	Available	NA	NA	NA	NA	NA	Available
Steam capacity D, t/h	320	320	320	272	320	320	180	320	240	320
Superheating temperature $t_{\text{superheat}}$, °C	560	555	560	560	560	560	560	555	555	560
Boiler efficiency η_{b}, %	92.554	92.378	91.854	92.032	92.057	92.267	91.998	92.150	91.978	92.062
Fuel flow B, m^3/h or t/h	23 525	21.252	23 702	20107	23654	23600	13315	21.320	16.015	23 648
The share of gas recirculation r	–	–	–	–	0.15	0.15	0.283	0.163	0.219	–
Recirculation gas flow rate V_{rec}, m^3/h	–	–	–	–	92955	91301	91231	91305	91304	–
Excess air:										
in the control section α_{con}	1.033	1.043	1.095	1.095	1.033	1.033	1.041	1.043	1.077	1.095
in exhaust gases α_{ex}	1.383	1.393	1.445	1.474	1.374	1.374	1.507	1.393	1.480	1.445
Temperature at the furnace outlet ϑ''_{f}, °C	1243	1168	1293	1226	1232	1230	1027	1178	1082	1291
Gas temperature, °C										
downstream of CS3 ϑ''_{cs3}	743	773	768	728	761	753	652	793	732	764
downstream of CS1 ϑ''_{ec1}	320	318	340	322	345	335	292	338	316	331
exhaust gas temperature ϑ_{ex}	144	157	152	144	154	150	134	166	157	148
Air temperature, °C										
downstream of the air heater t''_{ah}	37	70	37	37	37	37	37	70	70	37
hot air temperature t_{ha}	235	246	248	238	253	246	225	263	250	242
Water temperature upstream of EC1 t'_{ec1}, °C	270	236	289	280	290	266	249	231	231	266
Steam temperature °C										
before spray 1 t'_{spr1}	420	394	452	432	459	393	383	376	375	392
after spray 1 t''_{spr1}	397	393	402	398	399	376	377	376	375	377
before spray 2 t'_{spr2}	455	431	472	464	465	427	429	410	412	432
after spray 2 t''_{spr2}	406	422	397	402	398	387	405	409	411	393
before spray 3 t'_{spr3}	551	532	558	556	556	534	542	527	529	549
after spray 3 t''_{spr3}	530	530	525	529	525	526	537	525	529	526
Total flow rate for spray $D_{\text{spr}\Sigma}$, t/h	62.125	8.393	95.051	62.089	95.542	56.127	15.010	1.982	0.603	56.795

(1) Superheated steam pressure was $p_{\text{superheat}} = 13.729$ MPa. (2) Natural gas flow rate is given in m^3/h under normal conditions.

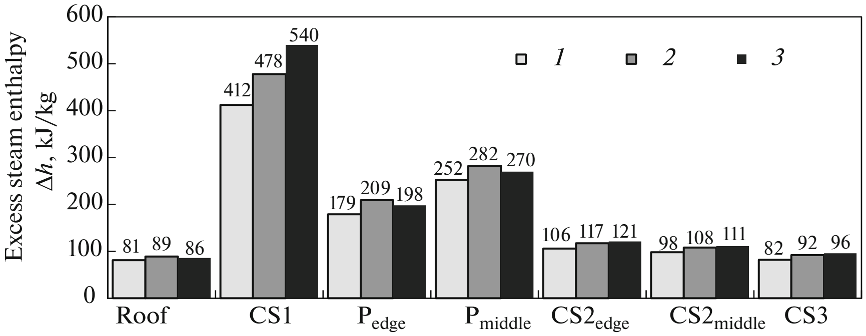

Fig. 2. Excess steam enthalpy in steam superheater stages. (*1*) Variant 1; (*2*) variant 3; (*3*) variant 5.

However, the existing condensing units cannot provide this condensate flow; therefore, we determined the boiler load at which two-stage natural gas combustion is still possible (variant 4). It is 85% of rated load; it is correlated with $D = 272$ t/h and $D_{\text{spr}\Sigma}$ slightly exceeding 62 t/h, which seems to be possible.

The boiler operation with 15% recirculation was then considered. It was assumed that products of combustion were selected by gas recirculation fans (GRFs) downstream of the economizer, were supplied to the air box of the boiler, and entered the furnace through the burners together with air. It was found that the boiler operation at rated load was impossible during gas combustion, since the calculated value of $t_{\text{superheat}}$ was 630°C at maximum possible condensate flow, $D_{\text{spr}\Sigma} = 65$ t/h. However, if we remove the limitation on the SCU capacity, we can achieve the value $t_{\text{superheat}} = 560°\text{C}$ at $D_{\text{spr}\Sigma} \approx 95.5$ t/h (variant 5).

The results for variants 3 and 5 show that both proposed environmental protection measures can be implemented with respect to the boiler if the capacity of condensing units is significantly increased. In addition, three spray-type attemperators will have to be replaced in each of the two symmetrical steam flows, since they were designed for much lower condensate flows. If this reconstruction is possible, it will inevitably lead to a significant reduction in the boiler operating economy. Thus, the efficiency is 0.5% lower for variant 5 than for variant 1 due to a growth in the water temperature upstream of the EC1 by 20°C and a decrease in the temperature difference in the economizer and the resulting increase in ϑ_{ex} from 144 to 154°C.

In addition, the increase in the flowrate for spray will inevitably lead to a decrease in the weight flow ρw in many superheater zones. According to [7], during the preliminary arrangement of the circuit of a superheater for rated steam capacity, ρw can be assumed to be 500 kg/(m^2 s) for convective high-pressure stages and 800–1000 kg/(m^2 s) for platens. The limitation is due to the fact that the lower value of the weight flow leads to a significant retardation of the cooling of tube metals and leads to a growth in the wall temperature and the likelihood of the failure of tubes increases due to oxidation or a decrease in their strength.

During the operation of the existing gas-fired boiler without recirculation (variant 1), the ρw values are 404 for CS1 and 565 for the edge platens and 794 kg/(m^2 s) for the middle platens. Certainly, the manufacturing plant carried out thermal-mechanical calculations for these stages; in addition, the long-term boiler operation has confirmed their reliability in practice. However, the level of the mass rate in the above-mentioned heating surfaces is lower than the regulatory guidelines. Therefore, it is also unreasonable to increase $D_{\text{sp}\Sigma}$ and additionally decrease ρw in terms of the conditions of operational reliability. This is important, since the conditions are worse for the performance of the metal of superheat tubes in variants 3 and 5 with increased $D_{\text{spr}\Sigma}$ values due to the significantly higher calculated values of steam temperature before sprays than those for the initial variant 1.

Consequently, there is the only possibility for the implementation of environmental protection measures, namely, to reduce the heating surface of a superheater. Figure 2 presents the calculated values of excess steam enthalpy Δh in the superheater zones for variants 1, 3, and 5. There are no recommendations on Δh in regulatory documents. However, the best practice of boiler equipment design and operation offers some insight on typical Δh values for separate stages. Δh of the roof superheater is usually 80 to 85 kJ/kg for U-shaped nongasproof boilers with high superheated steam pressure natural circulation, 145 to 210 kJ/kg for the cold convective stage, not more than 210 kJ/kg for the semiradiation platen stage, and not more than 145 to 165 kJ/kg for hot and outlet convective stages. It is evident that Δh for $\text{P}_{\text{middle},}$ especially for CS1, fall beyond this limit; their values are markedly higher.

However, in addition to the absolute Δh value, one should also take into account the regulation curve of the stage, i.e., the type of the dependence of Δh on the boiler load. The regulation curves of the cold convective stage and each of the platen stages for natural gas-based operating regimes with recirculation are shown in Fig. 3. Thermal boiler calculations at loads of 240 and 180 t/h were performed for their construction. As for variant 5, the absolute recirculation gas flow rate was maintained during these calculations; i.e., it was assumed that the GRF operating regime did not change. The rate of the curves in Fig. 3 indicates that Δh in the SH1 decreases with decreasing load; i.e., this stage has a convective regulation characteristic. In turn, the regulation characteristics of the platen stages are almost neutral, since Δh is almost independent from D. Therefore, from the perspective of the maintenance of $t_{\text{superheat}}$ at decreased loads, the role of platens is more important than that of the cold stage.

All of this shows that it is more preferable to reduce the heating surface of CS1 than the surface of semiradiation platens. In practice, it seems to be even easier to reduce the cold stage surface. In terms of design, it includes 32 tube banks in the direction of gas flow and consists of four identical loops. The tubes of the lower loops are made of St20 steel, while the tubes of the upper loop are made of 12KhMF steel. The preliminary calculations showed that it is necessary to reduce the heating surface of CS1 by two times, i.e., to two loops and 16 tube banks. At the same time, it is reasonable to retain the upper loop of 12KhMF steel, if possible.

However, this reduction of the cold stage surface will lead to a noticeable increase in the exhaust gas temperature, ϑ_{ex}. This is highly undesirable, especially if we take into account that ϑ_{ex} will increase by several degrees by itself during boiler operation with recirculation. In turn, this will lead to a decrease in the boiler efficiency.

WAYS OF INCREASING THE BOILER EFFICIENCY DURING THE IMPLEMENTATION OF ENVIRONMENTAL PROTECTION MEASURES

When staged combustion and flue gas recirculation are implemented in the boiler under consideration, it is necessary to expand a surface downstream of CS1 in the direction of gas flow simultaneously with the reduction of the surface of CS1 to maintain the operating efficiency of the boiler. It will be hardly possible to increase the surface of the regenerative air heater (RAH) due to the fixed size of the rotor. In addition, this measure is unreasonable, since it will lead to an increase in hot air temperature. Therefore, one should increase the heating surface of the economizer.

Analysis of the boiler design showed that it is possible to increase the surface of any of the economizer tube banks from above, since the existing gap is small between the bearing beams and tubes. However, it is possible to increase the surface of EC1 by one loop from below (under the beams). The existing EC1 includes a staggered counterflow section, two tubes in the coil, three loops, and 24 tube banks in the direction of gas flow. It is necessary to increase EC1 by 1/3, i.e., to four loops and 32 tube banks. The further increase is possible, but it is unreasonable, since this barely leads to a decrease in gas temperature, as was shown by preliminary calculations.

Thermal calculations were carried out for different regimes of boiler operation with the reduced surface of the cold convective stage and increased surface of EC1. The results of some of them are given in Table 1.

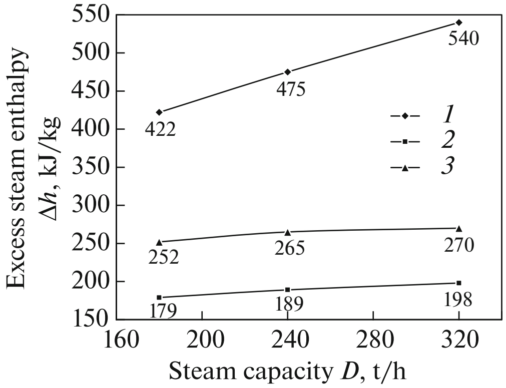

Fig. 3. Regulation characteristics of CS1 and platen stages. (*1*) CS1; (*2*) P_{edge}; (*3*) P_{middle}.

Variant 6 corresponds to the boiler operation at rated load during gas combustion with 15% recirculation. Here, the total flowrate for spray is slightly higher than 56 t/h, which can be adequately provided by the existing SCUs. The air temperature values before and after sprays became lower than those for the initial variant 1; i.e., the reliability of the performance of steam superheater tube metal should increase. However, the exhaust gas temperature increased by 150°C; at the same time, the boiler efficiency is almost 0.3% lower than that for variant 1. The recycle gas flowrate, V_{rec}, is 91300 m^3/h for this operating regime. For the other operating regimes with recirculation (variants 7–9), V_{rec} was maintained at this level with a high accuracy; i.e., it was assumed that the GRF operating regime did not change. The calculation for the minimum value $D =$ 180 t/h according to the PFD (variant 7) showed that $D_{\text{spr}\Sigma}$ was approximately 15 t/h for this regime. This means that the boiler load can be lower.

The operability of the reconstructed boiler on the basis of natural gas without recirculation was also studied. It was found to be possible at $\alpha_{\text{control}} = 1.033$, given that the load was 100%, which is in line with the relevant PFDs. In addition, the condensate flowrate for spray was approximately 25.5 t/h; i.e., quite a considerable decrease in the load is still possible under the regime with minimum excess air. However, at minimum load ($D = 180$ t/h), it is possible to obtain $t_{\text{superheat}} = 560°\text{C}$ in calculations only if α_{control} is increased to 1.18. Therefore, gas combustion without recirculation should be possible at all loads. As for the efficiency of these regimes, the calculated value of the efficiency is 0.2% higher at $D = 320$ t/h than that for variant 1 owing to a decrease in t'_{ec1} and a decrease in ϑ_{ex} to 140°C. However, if the load is decreased from a certain moment, the regimes without recirculation will be less efficient than now due to the necessity of increasing α_{control}.

The operation of the reconstructed fuel oil-fired boiler with recirculation is possible; however, according to the comparison of the results for variants 2 and 8, the efficiency at rated load is expected to be lower by approximately 0.2%. When the load is decreased, the fulfillment of condition $t_{\text{superheat}} = 555°\text{C}$ will be possible only if the excess-air coefficient is decreased; however, such regimes are also provided for in the current PFD. Thus, the discharge of the boiler to 240 t/h (variant 9) yields the calculated value $\alpha_{\text{control}} = 1.077$. It is correlated with the oxygen concentration $O_2 = 1.155\%$. This index is higher according to the current PFD: $O_2 = 2.8\%$. This is as it should be, since the PFD considers regimes without recirculation and $t_{\text{superheat}} = 555°\text{C}$ is achieved on the basis of a significant increase in α_{control}. Fuel oil-based operation at $D = 320$ t/h without recirculation was also considered. It is possible if $\alpha_{\text{control}} = 1.2$; however, the efficiency is lower in this case than for variant 8.

Variant 10 corresponds to the operation of the reconstructed boiler at rated load during two-stage natural gas combustion. It can be seen that this variant is quite realizable with respect to the total condensate flowrate for spray, which is approximately 57 t/h. At the same time, the $D_{\text{spr}\Sigma}$ value is sufficient for the boiler to be discharged to the level of up to 180 t/h. With respect to the operation of platens and CS2 and CS3, variant 10 may seem to be worse at first sight. Indeed, the temperature at the furnace outlet is 48°C higher here than that for variant 1 and the gas temperature downstream of CS3 is 21°C higher. However, the values of steam temperatures before and after sprays them became lower than those for variant 1. Therefore, the metal performance conditions in these zones were unlikely to have been significantly deteriorated. The calculated efficiency value during the implementation of two-stage combustion in the reconstructed boiler decreases approximately by 0.5% compared to the initial variant. Therefore, without including auxiliary power requirements, the regime of operation with recirculation is more efficient.

There is an additional measure to increase the efficiency of the boiler operation. For instance, this can be achieved by sealing the gas duct from the boiler to the RAH and adjusting the air heater seals during reconstruction. The tests showed that the total air inflows into the gas duct are approximately 35%. The inflow upstream of the control section (downstream of CS1) is minimal, while the inflow to the economizer is at the level of recommendations [6], and the inflow in the gas duct from the boiler to the RAH, $\Delta\alpha'_{\text{RAH}}$, and air overflows to the RAH are approximately 30%. It is quite realistic to reduce $\Delta\alpha'_{\text{RAH}}$ and $\Delta\alpha_{\text{RAH}}$ from 30 to 20%. In this case, according to the calculations, the boiler efficiency will increase by 0.25–0.26%. If we carry out these sealing works for the existing boiler, its efficiency will increase by 0.25%.

In conclusion, it should be noted that it is necessary to perform a more detailed design study on many issues when making a decision on the performance of boiler reconstruction for decreasing nitrogen oxide emissions. However, the conducted studies show that it is possible to reduce NO_x emissions to the normative values almost without reducing the performance indicators on the basis of a certain volume of the reconstruction of boiler heating surfaces.

CONCLUSIONS

(1) In long-standing gas-and-oil-fired boilers, it is possible to reduce the NO_x concentration in flue gases to the normative values by organizing two-stage combustion and flue gas recirculation. The replacement of the existing burners by new, low-emission ones is not always economically sound.

(2) As a rule, the implementation of environmental protection measures requires some reconstruction of heating surfaces. Specifically, for the BKZ-320 boiler that was considered in the article, one should reduce the surface of the cold stage of the superheater by 50% to provide the steam superheating temperature throughout the operating range.

(3) The implementation of environmental protection measures may lead to some decrease in boiler efficiency. The issues of maintaining and even enhancing the performance indicators should be individually solved in each specific case. Thus, with respect to the BKZ-320 boiler considered in this article, these issues can be solved by increasing the surface of the economizer and reducing air inflows and overflows in the gas duct section downstream of the economizer.

(4) The fundamental solutions that were used for the BKZ-320 boiler to reduce NO_x emissions can also be used for other gas-and-oil-fired boilers.

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