Assessment of the Possibility of NO_x Reduction in Smoke Gases of Steam Boilers DE-6.5/14 by Recirculation of Combustion Products

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1 Introduction

In recent years, the development of the fuel and energy complex of Russia has been rapidly increasing. In the developed Energy Strategy for the period up to 2035 for 2008–2020, a steady increase in energy consumption was noted, which amounted to 5.4% of the initial one, with an increase in the installed capacity of power plants by 11%. This is due to an increase in global demand for electrical energy from the electric transport sector, housing and communal services, the construction industry, as well as the expansion of existing and the formation of new energy-intensive industrial enterprises [1, 2].

With an increase in the capacity and expansion scale of energy enterprises, their load on the environment also increases [3]. One of the significant factors of impact on the environment is gas emissions from enterprises, among which nitrogen oxides are the leading ones. These substances contribute to the formation of smog and acid precipitation and also cause inflammatory and asthmatic processes in the human body. Therefore, the development of a technological solution aimed at reducing the formation of nitrogen oxides in the process of fossil fuel combustion is an urgent problem for ecology and energy [4, 5].

As is known, a high-temperature mechanism for the oxidation of molecular nitrogen by atomic oxygen in the combustion zone was proposed by Ya. B. Zeldovich:

$$O + N_2 = NO + N$$

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$$N + O_2 = NO + O$$

Under normal conditions, nitric oxide combines with oxygen with the subsequent formation of dioxide:

$$2NO + O_2 \rightarrow 2NO_2$$

The content of nitrogen dioxide in the exhaust gases of energetic enterprises depends primarily on the design features of burner arrangement and equipment, the schedule of heat loads, and the combustion mode. Therefore, the achievement of optimal results in the field of reducing the amount of nitrogen dioxide, as a rule, is carried out in two directions: improvement of the fuel combustion process and combustion products purification. The first area includes measures to reduce the combustion temperature, reduce the residence time of combustion products in the high-temperature area, and flue gas recirculation. Other equally effective methods are catalytic and non-catalytic reduction of nitrogen oxides. These methods are based on the injection of a reagent into the flue gas stream with the subsequent conversion of the substance under study into molecular nitrogen and water. At the same time, the most frequently used methods for reducing the concentration of nitrogen dioxides are recirculation of flue gases and the use of special burner arrangements given their high efficiency and low cost in comparison with other methods [6–8].

The introduction of a flue gas recirculation scheme for boilers TGM-84B, KVGM-180, TGME-464 made it possible to reduce emissions of nitrogen oxides by 40–60%. At the same time, the application of this method for reducing NO_x emissions has not been sufficiently studied on boilers of low steam capacity, such as DKVR-4/13 and DE-25/14GM. Therefore, the purpose of our study was to assess the possibility of using the flue gas recirculation method on DE-6.5/14 boilers [9–11].

2 Experimental Part, Results, and Discussion.

The studies were carried out at a gasified industrial heating boiler house, which is equipped with two DE-6.5/14 steam boilers and one water-heating boiler KVZH-4.0G. These boilers are equipped with GM-4.5 burner arrangements with a maximum heated capacity of 5.24 MW and gaseous fuel consumption by 510 m^3/h. The main fuel is gas, and the reserve is M100 fuel oil. To determine the real amount of nitrogen oxides formed during the combustion of gaseous fuel, process flow tests were carried out during the operation of the boiler unit in the load range of 25–100% from the nominal steam capacity. The test results are shown in Table 1 (Fig. 1).

During the tests the following was found:

1. Steam consumption through the boiler was determined by the direct balance;
2. Gas consumption was determined using a standard general boiler gas consumption meter, type “Logic” LNG-761;

Table 1 Operating parameters of the boiler unit st. No. 1, obtained as a result of operational testing

Parameter	Loading			
	25%	50%	75%	100%
Steam production, t/h	1.71	3.48	4.84	6.06
Fuel consumption (gas $Q_n{}^r = 34.09$ MJ/kg), m^3/h	154	278	380	473
Flue gas consumption, m^3/s	1.34	2.54	3.82	4.89
NO_x concentration in flue gases, mg/m^3	181.3	199.8	215.9	224.4
Mass emission of NO_x, mg/h	243.2	507.9	825.4	1099.1
Steam pressure in the drum, kgf/cm^2	7.0	7.2	7.3	7.6
Burner gas pressure, kPa	2.0	8.0	15.0	25.0
Flue gas temperature outside the boiler, °C	230	255	308	325
Gross boiler unit efficiency, %	76.03	85.71	87.21	87.73

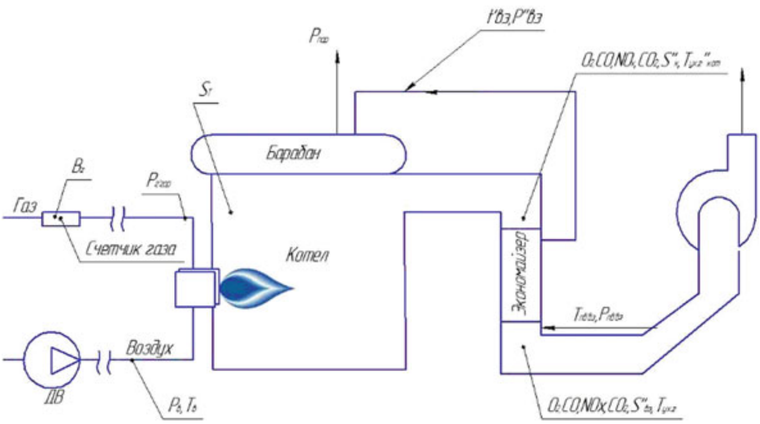

Fig. 1 Scheme of points for measuring the parameters of the boiler unit DE-6.5/14

3. In the calculation of technical and economic indicators, the flue gas temperature values determined using a portable gas analyzer of the DAG-500 type were used;
4. The concentration of nitrogen oxides varied depending on the steam capacity and amounted to 181.3–224.4 mg/m^3 for boiler st. No. 1.

After a series of experiments and data recording, it was proposed to use a simplified scheme with the supply of a part of the flue gases to the inlet air unit of the blower fan for the boiler station No. 1 DE-6.5/14. The implementation of these measures became possible when the unused Ø108 × 5 pipelines were converted into a process pipeline for flue gas recirculation. Cutting-in into the gas duct was carried out between the economizer and the boiler. The control of flue gases amount was carried out by flue damper. The results of repeated process flow tests in the boiler unit st. No. 1 are shown in Table 2.

Table 2 Operating parameters of the boiler unit st. No. 1, obtained using flue gas recirculation

Parameter	Loading			
	25%	50%	75%	100%
Steam production, t/h	1.73	3.42	4.86	6.15
Fuel consumption (gas $Q_n{}^r = 34.09$ MJ/kg), m^3/h	156	274	381	470
Flue gas consumption, m^3/s	1.36	2.53	3.88	4.90
NO_x concentration in flue gases, mg/m^3	172.6	190.3	212.9	226.5
Mass emission of NO_x, mg/h	235.5	481.3	825.9	1109.8
Steam pressure in the drum, kgf/cm^2	6.9	7.1	7.3	7.7
Burner gas pressure, kPa	2.0	8.0	15.0	25.0
Flue gas temperature outside the boiler, °C	232	260	315	329
Gross boiler unit efficiency, %	75.93	85.47	87.34	89.59

It was found by the calculation method that due to a decrease in the excess air and an increase in its temperature in front of the burner arrangement to 40 ºC, the efficiency of the boiler unit increased by an average of 0.4%. The results of measuring the concentration of nitrogen oxides at various operating modes of the boiler unit after using recirculation at 10% are shown in Fig. 2a. It can be seen that with the same heat output in modes at 25% and 50% load, the mass emission of nitrogen oxides after the use of recirculation decreases by 7.4 mg/h and 26.6 mg/h, respectively. At 75% loading, after recirculation was applied, the mass NO_x emissions remained virtually unchanged. With a further increase in fuel consumption, the indicator exceeded the

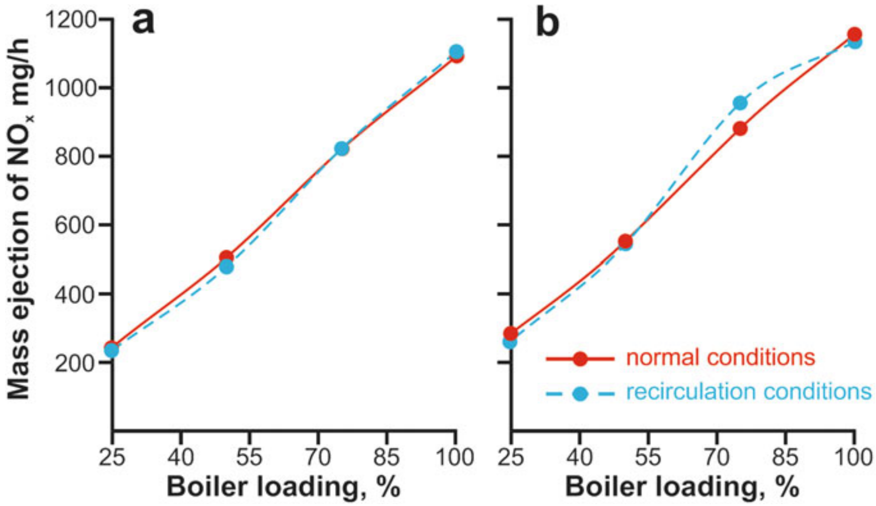

Fig. 2 Dependence of emitted nitrogen oxides amount of the boiler DE-6.5/14 loading: **a**—st. No.1; **b**—st. No. 3

nominal by 10.7 mg/h, which is explained by the insufficient blower discharge of the fan.

Successful experience in the implementation of these measures at the object under study allowed us to assume that the recirculation unit will be effective at the second identical boiler DE-6.5/14 on station No. 3. The results of process flow tests on the boiler unit st. No. 3 before and after the use of recirculation are given in Tables 3 and 4.

As can be seen from the results of Tables 3 and 4, operating parameters of boiler units on stations No. 1 and No. 3 differ significantly in some indicators. However, this does not prevent us from comparing the efficiency of using flue gas recirculation on this equipment. With the same heated capacity in modes at 25% and 50% load, the mass emission of nitrogen dioxide after recirculation decreased by 21.5 mg/h and 8.1 mg/h, respectively. At 75% load, after recirculation was applied, the mass NO_x emission value exceeded the nominal value by 8%, which indicates a malfunction in

Table 3 Operating parameters of the boiler unit st. No. 3, obtained as a result of operational testing

Parameter	Loading			
	25%	50%	75%	100%
Steam production, t/h	1.80	3.51	5.0	6.25
Fuel consumption (gas $Q_n{}^r = 34.09$ MJ/kg), m^3/h	162	293	400	499
Flue gas consumption, m^3/s	1.42	2.67	4.09	5.22
NO_x concentration in flue gases, mg/m^3	201.8	207.6	216.5	222.4
Mass emission of NO_x, mg/h	288.1	554.0	884.8	1160.7
Steam pressure in the drum, kgf/cm^2	6.6	7.0	7.3	7.8
Burner gas pressure, kPa	2.5	8.2	15.0	25.5
Flue gas temperature outside the boiler, °C	236	253	317	331
Gross boiler unit efficiency, %	76.08	82.03	85.59	85.76

Table 4 Operating parameters of the boiler unit st. No. 3, obtained using flue gas recirculation

Parameter	Loading			
	25%	50%	75%	100%
Steam production, t/h	1.79	3.55	4.95	6.20
Fuel consumption (gas $Q_n{}^r = 34.09$ MJ/kg), m^3/h	160	295	402	496
Flue gas consumption, m^3/s	1.40	2.70	4.06	5.16
NO_x concentration in flue gases, mg/m^3	189.8	202.0	236.5	220.9
Mass emission of NO_x, mg/h	266.6	545.9	959.8	1140.3
Steam pressure in the drum, kgf/cm^2	6.8	7.1	7.4	7.9
Burner gas pressure, kPa	2.5	8.2	15.0	25.5
Flue gas temperature outside the boiler, °C	234	256	310	328
Gross boiler unit efficiency, %	76.60	82.39	84.31	85.59

the boiler of station No. 3. With a further increase in fuel consumption, the indicator decreased compared to the nominal by 20.4 mg/h. The efficiency coefficient of boiler unit st. No. 3 at modes at 25% and 50% load increased by an average of 0.45%, however, at 75% load, the boiler unit worked worse than the nominal mode that gave an average by four indicators negative result in −0.13%. The results of measuring the concentration of nitrogen oxides at various operating modes on st. No. 3 boiler unit after using recirculation at 10% are shown in Fig. 2b.

Due to the complexity of the technological process of heat energy production and a sufficiently large number of factors affecting the effectiveness, it is not easy to determine a malfunction in the system. Therefore, to study the current situation, a conceptual model of the flue gas recirculation process was developed, shown in Fig. 3, which makes it possible to assess the degree of influence of qualitative factors and form a direction for further research.

The criterion for the optimality of this model is the NO_x concentration indicator in the flue gases, expressed using an objective function of the form [12, 13]:

$$Y = \max f(X, A, S, F) \quad (1)$$

while limiting the values of the variables X, $P_{y,}$ and Q.

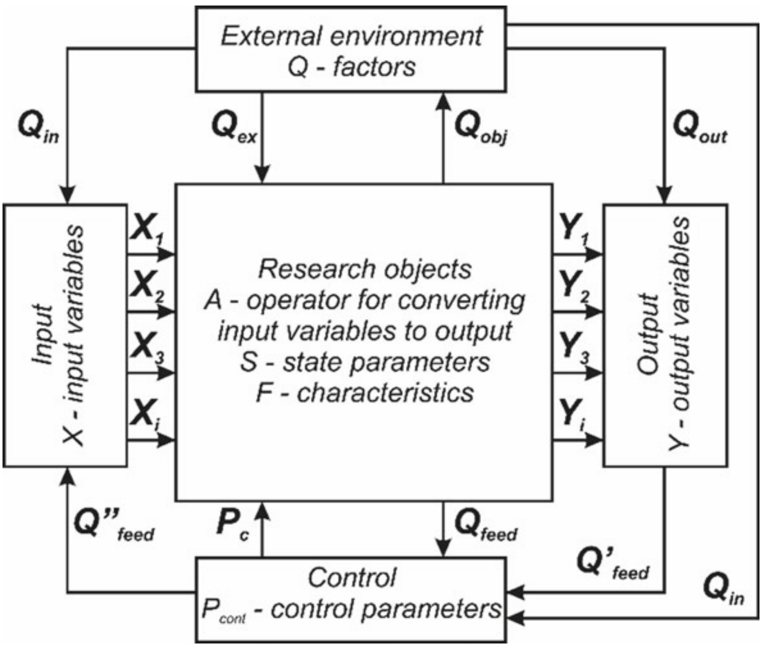

Fig. 3 Diagram of a conceptual model of a flue gas recirculation system

Table 5 The value of NO_x harmful emissions concentration when the load on the boiler changes from 25 to 100%

Object name	Load factor, %			
	25—A_1	50—A_2	75—A_3	100—A_4
Boiler station No. 1 meas. 1	181.3	199.8	215.9	224.4
Boiler station No. 1 meas. 2	172.6	190.3	212.9	226.5
Boiler station No. 3 meas. 1	201.8	207.6	216.5	222.4
Boiler station No. 3 meas. 2	189.8	202.0	236.5	220.9

In the course of the experiment, a change in the quantitative input variables X (gas and airflow rates, flue gas temperature, etc.) leads to changes in the output variables Y—the NO_x concentration.

Since the quantitative variables on boiler units st. No. 1 and No. 3 are practically equal, we needed to assess the impact degree on their value in the range of the load. Let the considered quantitative value X be influenced by the qualitative load factor A, which has four levels of values from 25 to 100%. For each level of factor A, the same measurement number of harmful emissions concentration X is carried out. The number of such measurements at each of the levels is $n = 4$. The measurement results are presented in the form of Table 5.

We believe that the aggregates of measurement data obey the law of normal probability distribution and to test the null hypothesis H_0 about the insignificant influence of factor A, we use the Fisher–Snedecor criterion [13, 14]:

$$F_{расч} = \frac{S^2_{факт}}{S^2_{ост}} = 15,02 \quad (2)$$

According to the Fisher distribution table for the significance level $\alpha = 0.05$ and degrees of freedom $k1 = k - 1 = 3$, $k2 = k\ (n - 1) = 12$, we find F_{crit}. (0.05; $k1$; $k2$) = 3.49. Thus $F_{crit.} < F_{calc.}$, which means that the load factor significantly affects the output concentration of nitrogen oxides and rejects the null hypothesis, which gives us the right to speak about the effectiveness of the proposed method of recirculation of flue gases on boilers DE-6.5/14 [9–11].

3 Summary

1. The process flow tests carried out in the industrial heating boiler house indicate that the use of the flue gas recirculation scheme on the DE-6.5/14 steam boiler is effective.
2. According to the results of the calculation, it was found that at the boiler at station No. 1 with the same heated capacity in modes at 25% and 50% load, the mass emission of nitrogen oxides after the use of recirculation decreases to

7.4 mg/h and 26.6 mg/h respectively. For boiler No. 3, these indicators changed and amounted to 21.5 mg/h and 8.1 mg/h at 25% and 50% load, respectively.

3. A conceptual model of the flue gas recirculation system has been built, based on which a qualitative factor influencing the quantitative indicators has been selected.
4. An analysis of variance was used to assess the significance of the load factor on the output concentration of nitrogen oxides. It has been established that the change in the amount of discharged harmful impurities in each of the boiler operation modes does not occur randomly but as a result of the directional effect of the proposed flue gas recirculation method.

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