Part 4

COMPLEX TECHNOLOGIES OF REDUCTION OF ENVIRONMENTAL POLLUTION FROM THERMAL POWER PLANTS

4.4. Complex reconstructive, operation and technological measures at gas and oil burning

4.4.2. Reduction of pollutant emissions from combustion of natural gas, fuel oil and water-oil emulsion in power boilers

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ABSTRACT

The article presents the results of experimental-theoretical study of natural gas and fuel oil combustion in steam power boilers, impact of operation and constructive factors on emissions of pollutants discharged with flue gases and methods of NO_x reduction in flue gases, their recovery to the molecular nitrogen.

KEYWORDS

Steam boiler, natural gas, fuel oil, oil, combustion, operation and constructive factors, nitrogen oxides, benz(a)pyrene.

In the process of fuel combustion in furnaces of steam boilers a variety of toxic substances are formed, which are then released into the atmosphere together with flue gases. Such substances in this case include, firstly, nitrogen and sulfur oxides, and, secondly, a number of products of incomplete combustion, in particular, polycyclic aromatic hydrocarbons (PAHC).

Formation of thermal nitrogen oxides, being the major NO_x contribution, from natural gas and fuel oil combustion is connected with a high temperature (>2000°K) in the flame front, while products of incomplete combustion are formed only in case of unsatisfactory performance of burners or unsuccessful combination of burners with steam boiler furnaces.

For a theoretical analysis, it was accepted to describe the flows of reacting gas mixture applied to the flows in the paths of boiler plants, using a complete set of Navier-Stokes equations, as well as the equations of chemical kinetics [1]. But because of the large dimensionality of the problem and the complexity of its solution, the use of appropriate programs for conducting mass parametric calculations is impossible, since the flow in the furnaces of steam boilers and further along the path has a space-indicative nature, and chemical reaction rates are determined by the level of temperature at a given point and a composition of a mixture. Therefore to describe the processes of nitrogen oxides formation and their subsequent transformation one-dimensional gas-dynamic model was applied.

At the first step of theoretical analysis, we'll consider one-dimensional flow of homogeneous mixture of ideal gases. The following chemical reactions take place between its components:

$$W \cdot \frac{dW}{dx} + \frac{1}{\rho} \cdot \frac{dP}{dx} = 0 \qquad (1)$$

$$\frac{w^2}{2} + \sum_{i=1}^{N} h_i(T)\gamma_i = H_0 \qquad (2)$$

$$P = \frac{\rho RT}{\mu}, \frac{1}{\mu} = \sum_{i=1}^{N} \gamma_i \qquad (3)$$

$$\frac{d\gamma_i}{dx} = \frac{1}{W} F_i(\gamma, P, T), i = 1,2,..., N \qquad (4)$$

Equations (1) and (2) are the equations of momentum and energy, (3) is the equation of state and the consequence of the Dalton's equation, (4) is the equation of chemical kinetics. Additional to these equations we add the mass continuity equation:

$$\rho WF = Q \qquad (5)$$

In these equations, *P, ρ, W, T* are pressure, density, velocity and temperature of the mixture; *N* – a number of different components of the mixture; *μ* – a molar mass of the mixture; *R* – universal gas constant; h_i *(T)* – an individual enthalpy of the *i*-component; γ_i – a molar-mass concentration; H_o – specific total enthalpy of the mixture; *x* – longitudinal coordinate; *F* – cross sectional area; *Q* – mixture flow rate through a cross-section.

The system (1) - (5) is supplemented by the initial and boundary conditions corresponding to a particular flow in the boiler furnace with appropriate furnace-burners devices.

At the traditional approach to the numerical simulation of combustion processes in the flame, the following assumptions are used:

- the process in the flame front is considered to be adiabatic;
- in the flame front the chemical equilibrium is reached.

Based on these assumptions, we define parameters (including a temperature of the combustion products and their composition) in the flare from the flame front, and further downstream. To determine the transformation of gas mixture composition at its flow along the path of the boiler plant there are generally used the following: either assumption of chemical equilibrium and thus the equations of chemical kinetics are replaced by the corresponding equilibrium equations (4), or a mechanism of chemical reactions being the most suitable in a particular case.

However, the results of the equilibrium calculations give the data, much different from the actual ones, because a number of factors (mixing, the mixture heating rate, residence time of regulatory mixture at a maximum temperature, effects of freezing of recombination NO_x reactions at temperatures below 2000 K etc.) are not considered that significantly affects the final nitrogen oxides concentration in fuel combustion products. Most true results for the components of fuel combustion products (namely, including toxic ingredients of NO, NO_2, N_2O, etc.) for different combustion conditions can be obtained using the equations of chemical kinetics (4). For their solution it was selected a mechanism of chemical transformations - a set of chemical reactions and their constant velocities, as well as the composition of the mixture at some initial point, then a simultaneous solution of the equations is searched (1-5) [1].

Application of theoretical analysis of fuel combustion process at different initial boundary conditions is shown in Fig. 1–3.

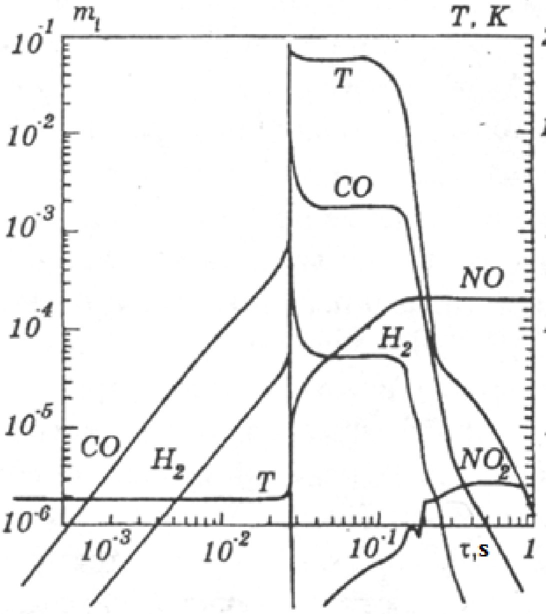

Fig.1. **Temperature and mass concentration of methane combustion product components in the air vs the time under conditions close to gas burning in the furnace of TGMP-314 boiler at α=1.**

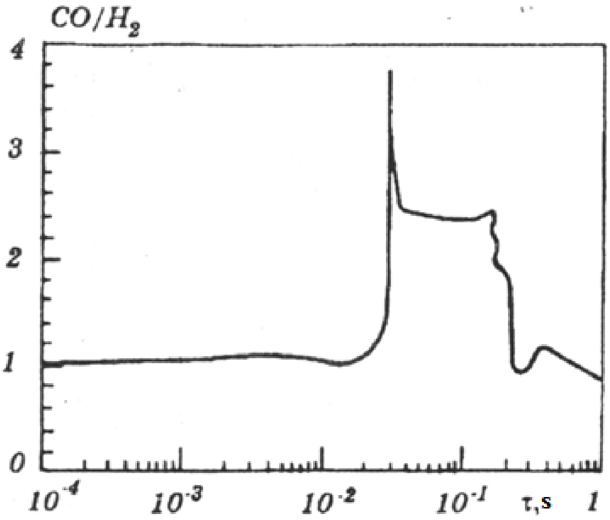

Fig.2. **Theoretical dependence: CO/H_2 mole fractions in methane combustion products in air under conditions typical for power boilers.**

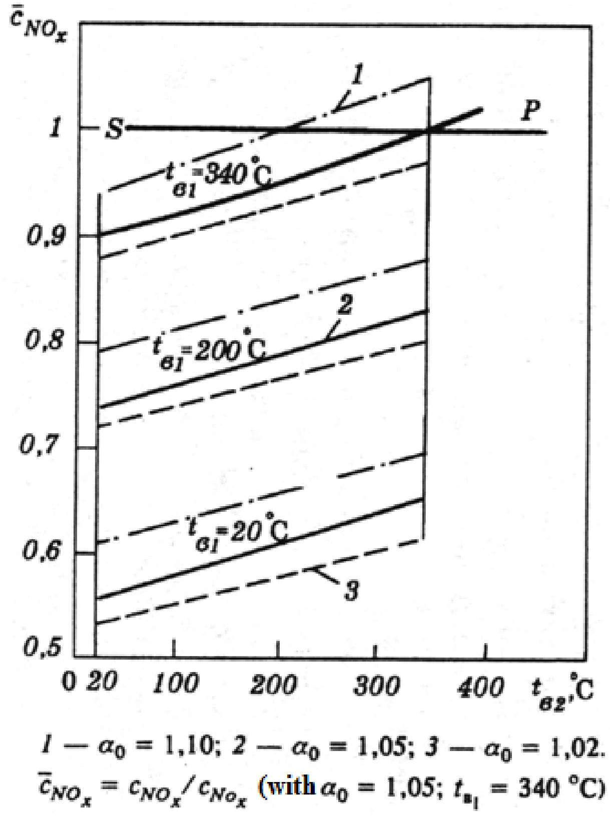

Fig.3. **Relative NOx concentrations in fuel combustion products vs the temperature of primary and secondary blast air and excess air at the two-stage natural gas combustion (α_1=0.81):** 1 – α_0 = 1.10; 2 - α_0 = 1.05; 3 - α_0 = 1.02.

From Fig. 1 follows that knowing theoretical dependences of parameters of various fuel combustion processes and their implementation methods significantly contributes to the understanding of their physical and chemical nature, helps to analyze the responses of various structural performances of furnace-burner devices as well as operation and technological factors on the efficiency of NOx reduction process, that allows to define, select, and implement in practice (of course with the feasibility study), the most rational solutions.

Conducted theoretical calculations of natural gas combustion process in TGMP-314 boiler at excess air of 1,01 and 1,04 are shown in table 1 and compared with experimental data, obtained at TGMP-314 boiler. Concentrations of the major mixture components (O_2, CH_4, H_2, CO and NOx) are measured in the gas samples, selected from crosscuts of convective superheater.

As follows from the data presented, there is some discrepancy between the calculated and measured values of H_2, CO and NO_x concentrations. To explain this fact, the following hypotheses are offered:

- H_2 and CO incomplete combustion products may occur in flue gases at rather low for operation excess air α = 1,01 due to imperfect mixing with the oxidant, so-called chemical underburning of fuel;

Table 1. **Content of the main reactive components in flue gases of TGMP - 314 steam boiler.**

α	Components, mole fractions				C_{NOx}, mg/m^3 (under normal conditions)
	O_2	CH_4	H_2	CO	
1,01	$\frac{0{,}001-0{,}003}{0{,}00238}$	$\frac{0}{10^{-15}}$	$\frac{0{,}002-0{,}003}{4\cdot10^{-6}}$	$\frac{0{,}002-0{,}003}{3\cdot10^{-6}}$	$\frac{260-280}{140}$
1,04	$\frac{0{,}009}{0{,}00812}$	$\frac{0}{10^{-15}}$	$\frac{0}{6\cdot10^{-7}}$	$\frac{0}{5\cdot10^{-7}}$	$\frac{325}{190}$

Note: the numerator is the test, the denominator is the calculation.

- when controlling the fuel combustion process in a production environment it is difficult to determine the actual value of O_2 microconcentration in flue gases, especially during fuel combustion in modes close to stoichiometric. Indirect determination of α with stable retention of combustion regimes, performed using "Optima Chrome", that works on the principle of high-precision determination of H_2 microconcentration in flue gases and approaches to unity of the correlation coefficient of H_2 and O_2, testifies about more complete matching of theoretical and experimental results.
- differences in C_{NOx} values in tests and calculations using the proposed procedure, may be due to some incompleteness of the kinetic model, for example, due to the fact that we have not considered the mechanism of fast nitrogen oxides.

In general, a parametric analysis of the fuel combustion process allows to reveal its basic regularities at variation of operation and technological methods with their quantitative assessment of environmental (NO, NO_2) and technical-economic indicators (CO, H_2, O_2, CO_2, H_2), that promotes the rational arrangement of fuel combustion.

During recent operation of steam boilers nothing has essentially changed in the practice of suppression of the nitrogen oxides formation, as still only different varieties of operation and technological environmental options and their constructive design at fuel combustion processes are implemented:

- extremely low excess air;
- improving the flue gas recirculation efficiency;
- varying the residence time of combustion products in the zone of maximum temperatures;
- lowering the maximum temperature and the residence time of the reacting fuel mass in it;
- stage fuel combustion;
- water injection and input of active additives to the zone of harmful substances generation for their suppression and neutralization;
- combination of different methods.

Comparison of different constructive and technological DeNOx measures applied in TGMP-204 boilers at traditional representation of experimental data is shown in Fig. 4. Here are shown NO_x concentrations vs excess air, indicating characteristic features of the fuel combustion process arrangement with regard to the environmental aspect: flue gas recirculation, both at traditional option, and using the reconstructed system of jets output from burners, water injection into the combustion zone and accompanying design features of burner execution.

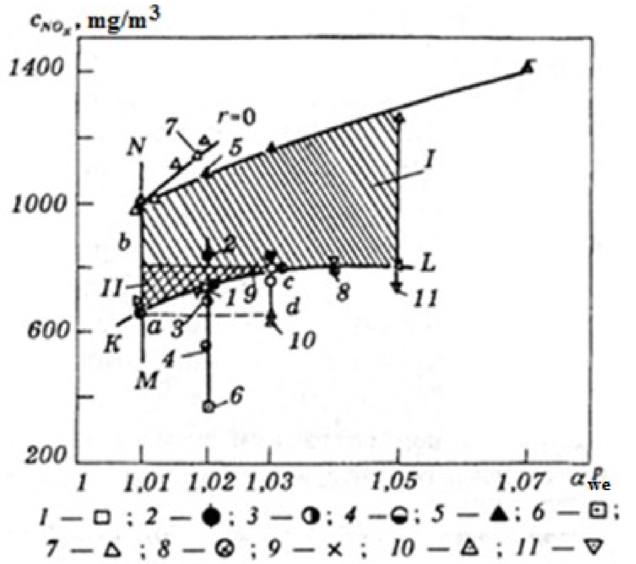

Fig.4. **Comparative efficiency of the effect of various design factors and ways of fuel oil burning in TGMP-204 boilers on NO_x concentration in flue gases:** I – area of combined design, operation and technological factors, which the increased NO_x concentrations are formed; II – the same as I, but with lower NO_x concentrations.

Quantitative values of nitrogen oxides, obtained at application of various operation and technological measures, necessary for significant reduction of NO_x concentration in flue gases, are usually much lower. They are limited by operational conditions of boiler plants. For example, for TGMP-204 steam boiler flue gas recirculation is maintained at a level of 8% at the rated load (PP_{GRF}=60/60%). Meanwhile, it's needed more deep reduction of nitrogen oxides concentration. Therefore, improving the efficiency of flue gas recirculation is achieved by additional reconstruction of the system of flue gas jets at the burner outlet with medium flow rate of recycled gases. Test results are presented in table 2.

Table 2. **Comparative tests of the effect of various design-technological measures to reduce the nitrogen oxides concentration in flue gases from the fuel oil combustion in TGMP-204 boilers**

Constructive and operation DeNOx measures	r, % (PP_{GRF})	C_{NOx}, mg/m^3
Basic option with vortex TKZ burners	8 (60/60)	730
Option with vortex burners and the recommended system of recycled gas jets output from burners	8 (60/60)	690
	12 (80/80)	540
Option with direct-flow-vortex burners	8 (60/60)	880
MPEI option with local moisture input into the combustion zone g=(3,3-4,4)% and direct-flow-vortex burners	8 (60/60)	340

Notes: r - flue gas recirculation, PP^A_{GRF}/PP^B_{GRF}; C_{NOx} – nitrogen oxides concentration in flue gases in crosscuts of water economizer (WE); PP – pointer position of the directing apparatus of the gas recirculation fan (GRF): stream A - numerator and stream B - denominator.

Experimental data relating to NO_x concentration are grouped in Fig. 4 in such a way, to analyze both individual and joint influence of excess air and flue gas recirculation on NO_x concentration. Shaded area (Fig. 4) corresponds to the nitrogen oxides concentration in flue gases of a steam boiler at mutual variation of α and r at the combustion process, meeting the regulatory requirements by conditions of fuel burning out and reliable boiler plant operation. This area contains a very small number of combinations of operation factors, limited by MN line from the left and KL line from the bottom.

MN line can move left or right, depending on the quality of fuel atomization and terms of its mixing with an oxidant, as well as by limitations of underburning and benz(a)pyrene concentrations. It's usually a little higher than the critical excess air; and in case of automatic control of the fuel combustion process, for example, at automatic maintenance of "fuel-air" ratio", using Optima Chrome system, the excess air is close to stoichiometric.

From the bottom the area of combinations of technological parameters is limited by KL line. Over KL line is the area of nitrogen oxides concentrations characteristic for normative operating conditions of boiler plants. Therefore, KL line characterizes the minimum concentration of nitrogen oxides in flue gases after implementation of technological DeNOx methods and at fuel combustion, meeting the regulatory limits of boiler plant operation.

From the represented characteristic curve of NOx concentration to design, operation and technological environmental measures (Fig.4) follows the interpretation of an equivalent significance of excess air and flue gas recirculation factor. Thus, consideration of the triangles abc and acd (Fig.4) shows, that reduction of NO_x concentration in flue gases from 780 mg/m^3 to 640 mg/m^3 at α''_{WE} = 1,03 and r = 8% and at fuel oil combustion in a steam boiler at the rated load with vortex burners, requires 10% increase in flue gas recirculation to the burner at α''_{WE}= const or decrease in α''_{WE} to 1,01 at r = const.

Thus, the same DeNOx efficiency are obtained in both cases: at oil combustion in TGMP-204 steam boiler operating on rated load, making 140 mg/m^3 , and at Δr (10%) and $\Delta\alpha''_{WE}$ (0,02) varying in the range α''_{WE} = 1,01 – 1,03. But the final decision should be taken after the feasibility study taking into account operating conditions of equipment.

Theoretical study on influence of technological parameters on NOx concentration and experimental data show the nonlinear C_{NOx} to α relationship. This factor is also valid for the dependence of the optimum air flow rate for both nominal and partial boiler load. Considering the relative decrease in $C_{NO_x}^{\alpha>ELEA}$ of a unitary part of changing $\Delta\alpha_{\alpha>ELEA}$ in the area of high excess air α''_{WE} = 1,03 – 1,05, we see that it is significantly different in magnitude in the area with smaller excess air α''_{WE} = 1,01 – 1,03, i.e.

$$\frac{\Delta C_{NO_x}^{ELEA}}{\Delta\alpha_{ELEA}} > \frac{\Delta C_{NO_x}^{\alpha>ELEA}}{\Delta\alpha_{\alpha>ELEA}}$$

or

$$\frac{0{,}780-0{,}640}{1{,}03-1{,}01} > \frac{0{,}800-0{,}780}{1{,}05-1{,}03}$$

The ratio 70>2 clearly testifies about the great importance of the excess air on suppression of NO_x formed at fuel combustion. These processes take place thy area of extremely low excess air (ELEA) or close to the stoichiometric.

Analysis of experimental and theoretical results shows that for a coming from the zone of increased concentrations of nitrogen oxides in flue gases to a zone of lower concentrations, located below KL line (Fig. 4), three assumptions are to be taken:

- firstly, to keep good condition of fuel burning out, avoiding the increased chemical and mechanical incomplete combustion of fuel;
- secondly, to ensure acceptable conditions of a temperature regime in the Low Radiation Section;
- third, to keep the temperature of steam reheat.

The first condition is realized by the improvement of fuel oil atomization process (for example, the use of metal-ceramic nozzles, preserving stable characteristics for a long period of exploitation), and while mixing the fuel with an oxidant in the burners.

The second condition is associated with reduced thermal stress in the Low Radiation Section of the steam boiler furnace, which is solved by raising the core flame (for example, switching from vortex burners to direct-flow-vortex ones), and also when injecting water into a zone of fuel combustion with intense generation of nitrogen oxides.

The third condition is implemented by technical-economic limitation of the upper level of flue gas recirculation, consisting 8% for the steam boiler of this type *(PP_{GRF}*=60/60%).

Fig. 2 shows the lines of damage zone from the area with the increased NOx concentrations to the smaller areas, (solved by various constructive activities based on recirculation of flue gases taking into account excess air): the first line at the air excess α''_{WE} = 1,05 and at introduction of recirculation gases to burners r' = 15,5%, The second line - the same as the first, but at α''_{WE} = 1,03 and the third line - the reconstructed system of output of recirculation gases from burners r = 12%, α''_{WE} = 1,02.

As shown by the experimental data, these proposals lead to reduction of NOx concentration in flue gas overriding KL line, which characterizes the minimum NO_x levels in flue gases, remaining, however, relatively high. Therefore, for TGMP-204 steam boiler when raising the core flame height along and implementing local metered injection of moisture, even more deep reduction of NOx concentrations is achieved.

Characteristic features of the flame in the furnace of TGMP-204 boiler when using direct-flow-vortex burners are change in the fuel burning out along the length, core flame upshift and increase in NOx concentrations in flue gases. NO_x concentration in flue gases when implementing this option in the original version, at oil combustion in the furnace of TGMP-204 boiler is 880°mg/m^3. Application of an additional local dosed injection of moisture into the combustion zone leads to a significant suppression of NOx formation processes in the boiler furnace. In case of water is injected in the amount of 6 – 8 t/h (that is 3,3 – 4,4% of the oil flow rate), flue gas is recycled to burners in the amount of r = 8% and α''_{WE} = 1,02, NOx concentration in flue gases is reduced to 340 mg/m^3. This corresponds to their reduction in flue gases more than twice under conditions of industrial exploitation of boilers. An essential advantage of moisture presence in the zone of active fuel combustion is reduction of carcinogenic substances in the fuel combustion products (in particular, benz(a)pyrene).

Availability of a large number of similar boilers in operation with various configurations of furnace and burner units and their arrangement allows to accumulate wide experience relating to effectiveness of primary environmental solutions. In particular, in steam TGMP-314 boilers, the burners are located on the walls of the furnace in special furnace extensions in the boiler bottom. Similar constructions of boilers were studied for solving various problems associated with an increase in the efficiency and reliability of their work.

However, differences in the furnace and burner units lead to different arrangement of the combustion process and, consequently, different emissions of toxic nitrogen oxides.

Experimental studies to identify the impact of operation and design factors on nitrogen oxides concentration in flue gases of steam boilers at gas and fuel oil combustion were conducted in TGMP-314 steam boilers. The boiler consists of: wall location of burners with steam mechanical atomizer "Titan" and burners "Pillard" (TGMP-314B), bottom arrangement of burners (TGMP-314P), cyclone furnace extensions (TGMP-314C).

The results of experimental studies on dependences of NOx concentrations in flue gases on the excess air and recirculation of flue gases at combustion of natural gas in steam TGMP-314 boilers are shown in Fig.5-7. As follows from Fig. 5, the higher level of nitrogen oxides concentrations is observed at combustion of natural gas in TGMP-314C boiler, it's a little lower in TGMP-314P, and a then a bit lower in TGMP-314B and TGMP-314. In case of natural gas combustion in TGMP-314C boiler, NO_x concentration varies from 1,11 g/m^3 to 0,84 g/m^3 with a decrease from α''_{WE} =1,075 to α''_{WE} =1,035 without supplying water into the combustion zone; the concentration decreases from C_{NOx} = 0,91 g/m^3 to C_{NOx} = 0,66 g/m^3 when inputting 4 t/h of condensate through the steam channels of oil injectors, i.e. ΔC_{NOx} is about 200°mg/m^3. For all steam boilers reduction of nitrogen oxides concentration with the excess air decrease is typical. Flue gas recirculation greatly impacts the reduction of nitrogen oxides concentration at natural gas combustion. For example, for TGMP-314C boiler at r = 10% the reduction of nitrogen oxides concentration by 24% is observed, at r = 7% it is reduced by 42 %.

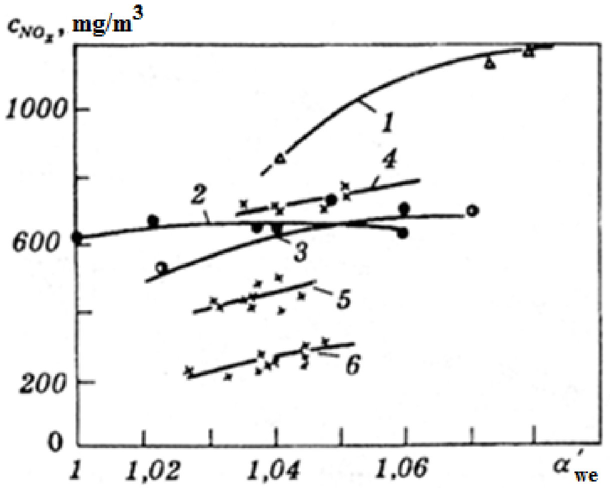

Fig.5. **NOx concentration in flue gases at natural gas combustion in TGMP-314 boiler, equipped with various furnace and burner units vs excess air and flue gas recirculation:** 1 – TGMP-314C, D_{SS} ≈ 900 t/h, r = 8%; 2 – TGMP-314P, D_{SS} ≈ 940-975 t/h, r = 0%; 3 - TGMP-314B with Pillard burners, D_{SS} ≈ 970 t/h, r = 12%; 4 - TGMP-314, D_{SS} ≈ 980 - 990 t/h, r = 2%; 5 - TGMP-314, D_{SS} ≈ 980 - 990 t/h, r = 8%; 6 - TGMP-314, D_{SS} ≈ 980 - 990 t/h, r = 12%, (SS - superheated steam)

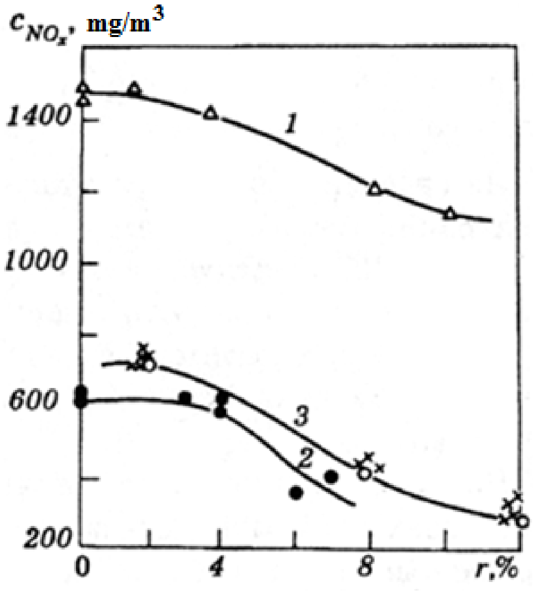

Fig.6. **NOx concentration vs flue gas recirculation rates at natural gas combustion in TGMP-314 boilers:** 1 – TGMP-314C steam boiler: D_{SS} = 820-900 t/h, α'_{WE} = 1.08; 2- TGMP-314P steam boiler: D_{SS} = 920-940 t/h, α'_{WE} = 1.03 – 1.04; 3 - TGMP-314 steam boiler: D_{SS} = 980-990 t/h, α'_{WE} = 1.04.

According to the test results (Fig.6) in case of fuel oil combustion NOx concentration in flue gases is the highest for the steam boiler TGMP-314C, and then it is lower for boilers TGMP-314P, TGMP-314B, TGMP-314, correspondingly. At steam spray of fuel oil and its combustion in TGMP-314TS boiler, NO_x concentration is changed to 1,24 g/m^3 at α''_{WE} = 1,070, to 0,82 g/m^3 at α''_{WE} = 1,020, and to 0,82 g/m^3 at α''_{WE} = 1,020. When inputting 4-5 t/h of water in the combustion zone, NOx concentration decreased from 1,05 g/m^3 to 0,86 g/m^3 at excess air change from α''_{WE} = 1,075 to α''_{WE} = 1,05. Reduction of NO_x concentration due to water injection into the combustion zone made ΔC_{NOx} = 200°mg/m^3 in this range of the excess air.

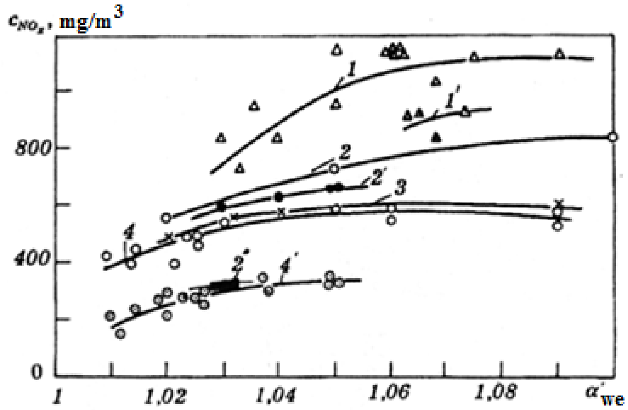

Fig.7 **NOx concentration in flue gases in TGMP-314 boiler at combustion of fuel oil depending on design, operation and technological factors**: 1 – TGMP-314C boiler, D_{SS} = 950-975 t/h, r = 3-5%; 1' – the same as 1, but with water injection into the combustion zone; 2 – TGMP-314P steam boiler (n_b = 8 pcs.), D_{SS} = 970-980 t/h, r = 0%, $\bar{G}$ = 0; 2' – TGMP-314P, r = 10%, $\bar{G}$ – 0; 2" – TGMP-314P, r = 10%, $\bar{G}$ = 10%; 3 – TGMP-314B steam boiler, Pillard burner, D_{SS} = 970 t/h, r = 8%, $\bar{G}$ = 0; 4 – TGMP-314 steam boiler, D_{SS} = 980-1000 t/h, r = 8%, $\bar{G}$ = 0; 4' – TGMP-314, r = 8%, $\bar{G}$ = 6%.

The lowest NOx concentration in flue gases is observed in TGMP-314 boiler. Wall burners with mechanical-vapor nozzles of Titanium type (n = 16 pcs.) are arranged in two tiers on the front and back sides of the furnace. TGMP-314 steam boiler, with wall layout of burners, has a good aerodynamic configuration of a structural assembly of air distribution, consisting in the uniform distribution of air among the burners. Here it is comparatively easy to implement the fuel combustion mode with extremely low excess air (α_{arr}=0,98; $\Delta\alpha_{fur}$=0,04; a'_{we} =1,02), allowing to have comparatively low nitrogen oxides concentration for the first boilers of TGMP-314 series and to realize a high-performance combustion process.

Table 3. **Comparative tests of the effect of various design and technological measures on reduction of NOx concentration in flue gases at natural gas combustion in TGMP-314 boiler.**

Constructive and operation DeNOx activities (reference designation of the fuel combustion method)	α'_{WE}	C_{NO_X} mg/m^3
Natural gas combustion without injecting moisture into the fuel combustion zone	1,035	496
Steam supply (G_{s1} = 2,56 t/h) through the steam injector channels through all burners (fuel combustion mode recommended by regime charts - the original version)	1,040	521
Steam supply (G_{s1} = 1,28 t/h) through the nozzles of the lower tier of burners	1,030	473
Steam supply (G_{s1} = 1,28 t/h) through the nozzles of the lower tier of burners	1,042	446
Steam supply (G_{s2}= 3 t/h) into blasting air	1,040	389
Moisture supply (G_{s1}=1,28 t/h + G_w = 5,5 t/h) through the nozzles of the lower tier of burners into the boiler furnace	1,035	366
Natural gas combustion of under MPEI method with combined moisture supply into the fuel combustion zone (G_{s1}=1,28 t/h + G_w = 5,5 t/h) through the nozzles of the lower tier of burners (+ G_{s2} = 3t/h) into blasting air	1,035	269

Notes: α'_{WE} - excess air at the water economizer inlet; C_{NOx} – NOx concentration in flue gases at the water economizer inlet.

Table 3 shows the experimental data of comparative tests relating to the effect of various design, operation and technological measures for reduction of NOx concentration in flue gases from natural gas combustion in TGMP-314 boiler (boiler #4 at Kashirskaya SDPP). The experiments were conducted at a rated load with a constant flue gas recirculation factor r = 6% and reconstructed gas distribution assembly of burner units in the primary air stream with axial outlet of gas jets. The analyzed flue gas samples were taken from the section of the convective shaft from four probes, that allows not only to determine average values in half-furnaces and steam boiler as a whole, but also to assess the impact of arrangement of fuel combustion processes on distortions along the gas path. Nitrogen oxides concentrations were determined by a gas analyzer termotesto–33. Along with NOx concentrations there were determined parameters of the boiler plant, which allowed to evaluate technical-economic performance at various modes of fuel combustion.

Fig. 7 presents the experimental NOx concentration in flue gases at the different methods of fuel combustion. As follows from the experimental data, the input of moisture in the gas combustion zone differently affects NOx concentration. The most significant reduction of NO_x concentrations is achieved applying MPEI fuel combustion method with a'_{we}=1,035, r = 6% and combined moisture input into the combustion zone: supply of steam G_s= 1,28 t/h and water G_w= 5,5 t/h through the nozzles of the lower tier with C_{s2} = 3 t/h into blasting air.

Compared with the original option of C_{NOx}= 521 mg/m^3, natural gas combustion under the new method reduces this value to C_{NOx} = 269 mg/m^3, which corresponds to 48% NO_x reduction in flue gases compared with initial variant.

The benefit of fuel combustion with the local dosed injection of water into the fuel combustion zone with intense nitrogen oxides generation is that this method can be applied independently from other constructive, operation and technological measures for NOx emissions reduction discharged into the atmosphere with flue gases.

Results of realizing operation and technological DeNOx measures at fuel oil combustion with water injection of 6-10% of the mass flow rate in TGMP-314 steam boilers are shown in Fig.7. For TGMP-314C and TGMP-314 steam boilers the dosed local injection of water into the combustion zone of the flame under the method [4] leads to an additional reduction of NOx concentration in flue gases by 200 mg/m^3 and is a low cost measure.

In case of TGMP-314 steam boiler with wall two-stage arrangement of burner devices (16 turbulent dual-channels TKZ burners with steam mechanical nozzles of Titan type), water supply into the flame combustion zone in a quantity of g = 6-10% of the oil flow rate leads to reduction of nitrogen oxides concentration up to 0,15—0,25 g/m^3 at fuel oil combustion with extremely low excess air ratio α = 1,015–1,025. In this case, a double reduction of nitrogen oxides concentrations under industrial operating conditions of TGMP-314 boiler.

When applying moisture in the hot-air-path (at fuel oil combustion) [5] the nitrogen oxides suppression is a smaller value as compared with a local dosed input of water into the fuel combustion zone with intense generation of nitrogen oxides.

Combustion of a fuel mixture (44—46 t/h of oil and 26,5—28,6 thousand m^3/h of natural gas) in TGMP-314C boiler with steam atomization of fuel oil showed that nitrogen oxides concentration is changed from 0,93 g/m^3 to 0,66 g/m^3 at α'_{we} =1,12, from 0,66 g/m^3 to C_{N0x} = 0,54°g/m^3 at α'_{we} = 1,05 at water supply into the combustion zone and in the same α'_{WE} range (Fig.4). Reduction of NO_x concentration in these experiments made ΔC_{NOx}=270°mg/m^3 at α'_{we} = 1,05 and ΔC_{NOx}=120°mg/m^3 at α'_{we} = 1,12. This experience is also interesting because it allows to compare the excess air with water injection. The same environmental effect for the steam boiler in reducing nitrogen oxides is achieved either by water injection of 4-5 t/h (less than 6% of the fuel consumption) in the cyclone furnace extensions, or by decreasing the excess air by α'_{we} = 0,07. The total effect of NO_x suppression due to lowering excess air and water injection is 390 mg/m^3 or 42%.

Local dosed injection of moisture in the combustion zone of TGMP-314 power steam boilers leads to a further reduction of nitrogen oxides concentration in flue gases making 200 mg/m^3. The method is easy to implement at commercially operating steam boilers. It is mobile, low-cost and applicable when burning various fuels and fuel mixtures (oil + gas),for various design solutions of furnace and burner units of steam boilers. This method is indirectly implemented at industrial operation of steam boilers with steam mechanical nozzles, when while burning natural gas the steam is supplied in order to preserve high reliability of the boiler operation at the emergency shutdown of natural gas and switch to burning fuel oil.

Similar positive attributes marked in case of burning water-oil emulsion, are characteristic for description of water-fuel emulsions based on crude oil. When further reduction of NOx concentration is necessary (if the resource for primary environmental operation and technological measures is exhausted) there can be applied a method of flue gas cleaning (secondary environmental measures), which consists in the oxidation and absorption of nitrogen oxides from flue gases [6].

One of the sources of benz(a)pyrene formation are fuel combustion processes, not providing complete combustion. Especially favorable conditions for the formation of benz(a)pyrene and other carcinogenic polycyclic aromatic hydrocarbons (PAHs) are created in the combustion process, occurring at high temperatures with lack of air.

When burning fuel with extremely low excess air as well as at staged combustion, there is a real danger of a sharp increase in benz(a)pyrene concentrations in flue gases.

Experimental benz(a)pyrene concentrations in flue gases from natural gas combustion in TGMP-204HL boiler with extremely low excess air α=1,01–1,0 and at H_2=0,025–0,03, corresponding to deep suppression of NOx concentration, as well as at H_2=0,002–0,005 and at moisture supply into combustion zone are shown in Fig. 8. As follows from the experimental data, at traditional method of fuel combustion in the zones with extremely low excess air and chemical micro underburning, along with deep reduction of NO_x concentration in flue gases, there is a sharp growth of $C_{20}H_{12}$ concentration, reaching 311 mkg/100m^3.

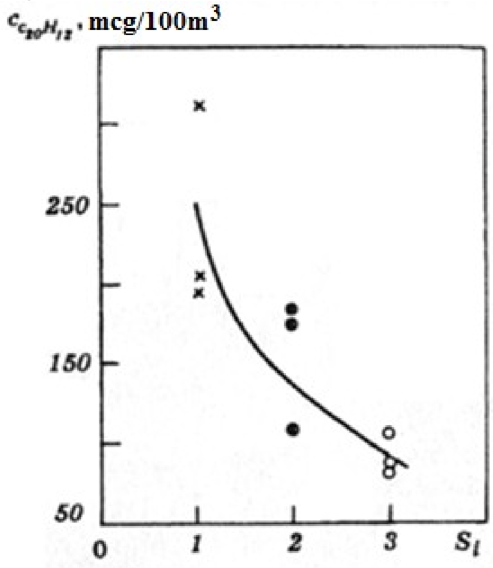

Fig.8. **Benz(a)pyrene concentration in flue gases at combustion of natural gas in TGMP-204HL steam boiler operating at the rated load depending on the ways of fuel combustion (S_i):** 1 – fuel combustion with extremely low excess air α^P_{we} = 1.01-1.015, H_2 = 0.025-0.030% vol. ("Optima-Chrome" is not included into the control system of combustion process); 2 – the same as 1, but with automatic regulation of fuel-air ratio with the inclusion of "Optima Chromium", H_2 = 0.002-0.005% vol. 3- the same as 2, but with water fed into the fuel combustion zone under MPEI combustion scheme.

Experimental benz(a)pyrene concentrations in flue gases applying different methods of fuel oil combustion in TGM-84 boilers are shown in Fig.9. It shows that the moisture input into the combustion zone in any form (either an independent separate input, or with water-oil emulsion) has a very positive effect on reduction of $C_{20}H_{12}$ concentrations in flue gases. The presence of moisture in the combustion zone, unlike other operation and technological measures, such as lowering excess air and flue gas recirculation, has a unidirectional impact on both reduction of NOx and benz(a)pyrene concentrations.

Experimental benz(a)pyrene concentrations in flue gases applying different methods of natural gas and fuel oil combustion under different technologies implemented in steam boilers are shown in Fig.10. The figure shows, that, both at combustion of natural gas or fuel oil, the lower benz(a)pyrene concentrations are characteristic for fuel combustion modes with large values of the excess air, and at their equal values - due to moisture injection into the combustion zone or in case of burning fuel or water-oil emulsion.

Thus, arrangement of natural gas and fuel oil combustion process in furnaces of steam boilers significantly affects benz(a)pyrene concentration in flue gases. Moreover, fuel combustion applying environmental operation an technological measures aimed at reduction of NOx concentration can lead to increased benz(a)pyrene concentrations. Therefore, a final choice of the fuel combustion process should be made at the joint estimation of C_{NOx} and C_{C20H12}.

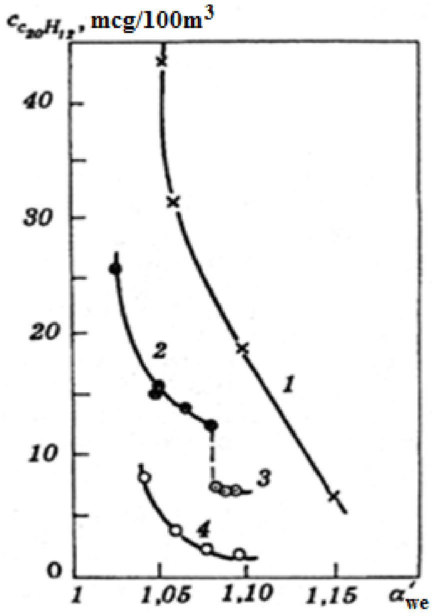

Fig.9. **Benz(a)pyrene concentration in flue gases of TGM-84 steam boiler operating at the rated load depending on the method of fuel oil combustion:** 1 – original mode of fuel combustion without moisture injection into the fuel combustion zone; 2 –TGM-84B steam boiler (boiler №3 at Arkhangelskaya CHPP), fuel oil combustion with steam atomization; 3 – combustion of water-oil emulsion with W^P = 7%; 4 – fuel oil combustion with 10% of moisture fed into the combustion zone.

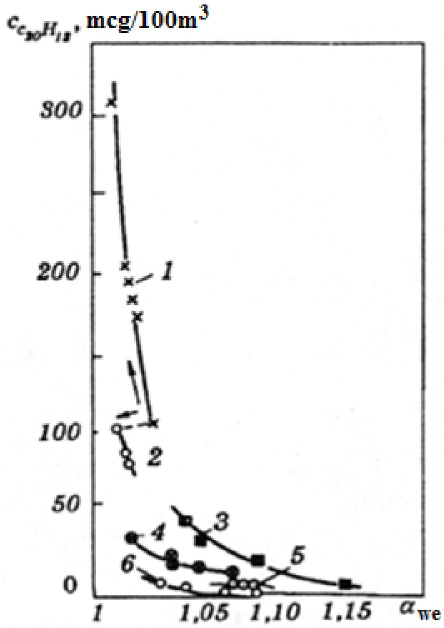

Fig.10. **Influence of constructive and operation factors on benz(a)pyrene content in flue gases of steam boilers in case of natural gas and fuel oil combustion:** 1 – TGMP-204CHL steam boiler (boiler №5 at Surgutskaya SDPP-2), natural gas, G_w = 0; 2 – the same as 1 at G_w = 0.640 t/h; 3 –TGM-84 steam boiler, at fuel oil combustion, fuel oil steam atomization; 4- ТГМ-84B steam boiler, fuel oil, fuel oil steam atomization; 5 – the same as 4, at combustion of water-oil emulsion W^P = 7%; 6 – the same as 3, at 10% of moisture injeced into the fuel combustion zone.

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