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ENERGY-ECOLOGICAL ASSESSMENT OF THE BOILER EQUIPMENT MODERNIZED WITH THE JET-NICHE TECHNOLOGY

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The results devoted to the issues of energy-ecological assessment of industrial boiler equipment with jet-niche combustion technology are given in the paper. The basic principles underlying this technology include: rational distribution of fuel in the oxidant stream; stable adjustable structure of fuel, oxidant and combustion products; self-regulation of the fuel mixture composition in the zone of the torch stabilization when the unit load changes. As of today, a large number of industrial gas-burning equipment has been modernized by jet-niche technology, including: boilers, furnaces, dryers, metallurgical facilities, etc. The results of industrial implementation of the technology allowed to accumulate a significant amount of technical information and gave the possibility of preliminary environmental assessment during the modernization of gas combustion equipment. As practice shows, at the present stage the main direction of the technology improvement is to enhance its environmental performance. The influence of the main regime and technical parameters of fire equipment on its emission indicators is established in the paper. Possibilities for reducing nitrogen oxides by primary technological methods, the simplest and most effective of which is the introduction of recirculation gases into the furnace space, have been identified. According to the results of the analysis of emission indicators of the modernized fire equipment with a capacity of 0.5–60 MW, data to estimate the emission indicators of low and medium power boilers depending on the main influencing factors, namely, unit size, excess air ratio and boiler load were obtained. The influence of the introduction of recirculation gases into the furnace space on the level of nitrogen oxides concentration is also taken into account. The efficiency of application of the recirculation gases introduction scheme into the primary air flow in comparison with combustion technologies based on vortex burners is shown. According to the results of the industrial experiment, the energy efficiency of the proposed measures was established on the example of the dependences of efficiency on the load of boilers PTVM-50 and KVGM-20.

***Keywords**: gaseous fuel, jet-niche technology, nitrogen oxides, regime parameters, ecological characteristics, gas recirculation.*

Introduction

Currently, Ukraine has the highest integrated indicator of negative man-made loads on the environment in almost the entire territory among European states. It is known that energy is one of the main sources of environmental pollution, so understanding the patterns of harmful substances formation and the possibility of forecasting their emission is one of the main issues of ensuring environmental safety standards nowadays [1].

Nitrogen and carbon oxides are among the main harmful elements formed during the burning of natural gas. As is known, nitrogen oxides are a component of the atmosphere, but the greenhouse activity of nitrous oxide is 298 times higher than that of carbon dioxide. The maximum allowable concentration of nitrogen dioxide MAC_{NOx} in the surface layer of air is 0.085mg/m^3, while for NO MAC_{NO}=0.6 mg/m^3 [2].

It is known that NO_x formed in the combustion process usually arise either from the thermal fixation of atmospheric nitrogen in the combustion air, leading to the formation of "thermal NO_x", as originally postulated by Zeldovych (1946), or from the combination of hydrocarbon fragments and atmospheric nitrogen in combustion zone, resulting in the formation of "prompt NO_x", first established by Fenimore (1971), or from the conversion of chemically bound nitrogen in the fuel, resulting in "fuel NO_x". The formation of thermal NO_x is believed to be influenced by such factors as the presence of free oxygen in the combustion zone (O_2), temperature, pressure and residence time in the high-temperature zone. As for fuel NO_x, their formation depends on such factors as the nitrogen content in the fuel, the total amount of excess air, and the relative distribution of primary and secondary air for combustion [3].

It is known that there are two fundamentally different ways of reducing emissions of toxic gaseous substances [4]:

– passive – cleaning of flue gases using special plants mounted behind the boiler in the area between the last heat-receiving surface and the chimney;

– active – suppression of the NO_x emission process at the initial stage of their formation.

One of the most common "active" methods of suppressing the emission of nitrogen oxides is the introduction of part of the waste gases into the high-temperature zone of the combustion chamber by recirculation of combustion products. From the point of view of ensuring environmental indicators, the recirculation scheme has proven its effectiveness for a wide range of fire engineering equipment. It is widely used both for combustion chambers of gas turbine units [5] and for solid fuel boilers [6], where due to saturation with combustion products of pellet fuel before feeding into the furnace, it was possible to improve the burnout indicators and the combustion process stability. Gas recirculation is considered an effective mechanism for regulating the maximum combustion temperatures, and when providing staged combustion using non-stoichiometric burners, it is possible to ensure a reliable process of fuel-consuming equipment operation with further compliance with environmental indicators [7, 8]. When using synthesized gas fuel obtained from coal as an oxidizer, the CO_2/O_2 mixture is more environmentally friendly compared to N_2/O_2 one, which can be implemented by using recirculation of combustion products [9].

Based on this, currently one of the most common regulatory measures and those that are easily implemented and contribute to the reduction of nitrogen oxide emissions is the reduction of the excess air (Low Excess Air – LEA) in the furnace. As is known, as a result of reducing the oxygen content in the torch, the formation of both thermal and fuel NO_x is suppressed, which is why this measure can be applied when burning various types of organic fuel [10].

Passive methods of reducing nitrogen oxides include selective catalytic and non-catalytic nitrogen reduction technologies. With this cleaning of nitrogen oxides, the content of NO_x in combustion products is reduced by an average of five times. However, there are significant disadvantages of the method, such as the high cost of catalysts and equipment, corrosion of materials, high operating temperature, and limited service life of the catalyst [11]. However, its high efficiency, relatively simple installation, and reasonable operating costs make it a perfect tool of removing NO_x from flue gases.

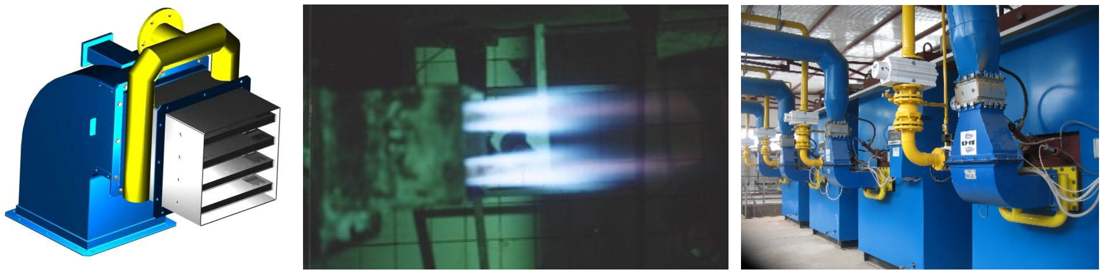
Therefore, all NO_x removal methods have their advantages and disadvantages. However, in the overall picture, each method alone or in combination significantly improves the environmental performance of the equipment. Further research into NO_x emission control measures will obviously address the issues of creating simpler technical solutions, reducing the cost of these measures, and increasing the efficiency of NO_x conversion at lower temperatures.

Further material will be devoted to the prospects of applying primary measures to suppress the emission of nitrogen oxides by fire engineering equipment when implementing domestic efficient burner systems based on jet-niche technology (JNT).

Main body

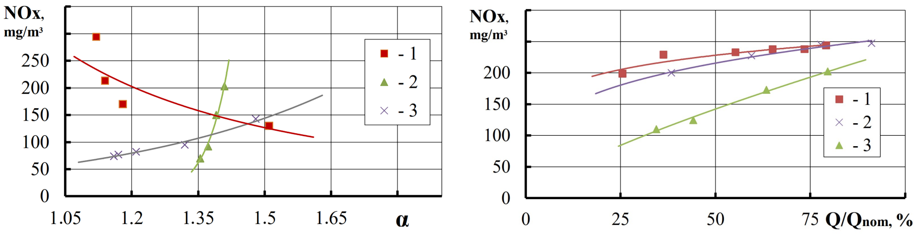
Recently, the existing equipment has been modernized in order to reduce nitrogen oxides. According to the results of the study, it was proved that the efficiency of reducing the emission of nitrogen oxides is most affected by the fuel combustion technology. From the point of view of the canonical principles of minimizing NO_x concentrations, such as preliminary mixture formation, staged combustion and direct-flow aerodynamic flow scheme of the oxidizer, the burners developed at National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", in which, in particular, jet-niche combustion technology is used, are recognized as promising (Fig. 1) [12].

The main principles underlying the technology are as follows: rational distribution of fuel in the oxidizer stream; stable adjustable flow structure of fuel, oxidizer and combustion products; self-regulation of the composition of the fuel mixture in the torch stabilization zone in a wide range of changes in fuel and oxidizer flow rates, high combustion intensity, stability and efficiency of the process in the working range of changes in thermal power. As of 2021, on the basis of JNT, significant experience has been gained in the energy-ecological modernization of boiler equipment with a capacity of 0.5–125 MW.



a b c

Fig. 1. Jet-niche fuel burning technology:
a – burner, b – open gas torch, c – arrangement of burners on gas-consuming equipment



a b

Fig. 2. Dependence of the concentration of nitrogen oxides on the main technological parameters in boiler equipment with JNT depending:
a – depending on the coefficient of excess air (1 – PTVM-30; 2 – DKVR-10; 3 – KVGM-20);
b – depending from boiler load (1 – KVGM-20; 2 – TVG-8; 3 – KVG-7.56)

It should be noted that there is a "National plan for reducing emissions from large fuel combustion plants" in Ukraine [13], which directly applies to thermal power plants with a thermal capacity of 50 MW and above and is designed for gradual implementation until 2032 inclusive. Thus, the first stage of its implementation considers the adoption of primary technological measures, and the second one – the introduction of secondary technologies based on the process of nitrogen oxides reducing. Among the primary measures to reduce nitrogen oxides, the use of recirculation of combustion products in the fire equipment of the heating plant based on the highly efficient energy-ecological technology of JNT combustion can be considered one of the most effective ones.

The results of earlier studies indicate that the occurrence of nitrogen oxides (NO_x) is significantly influenced by: the coefficient of excess air in the furnace (α_f), productivity (D_0) and the boiler load ($N=(D/D_0)\times100\%$) [14], as well as poor organization of fuel burning, i.e. existent misfires.

Fig. 2 shows the dependence of the concentration of nitrogen oxides on the main technological parameters in the boiler equipment modernized with the help of JNT. From the point of view of forecasting emission characteristics, the normalized indicators of nitrogen oxides NO_x^{norm}, which are determined in the absence of all operational influences, at $\alpha=1.0$, are of practical importance. The value of the critical excess air $\alpha_{cr1}>1.0$ (hereinafter, α_{cr}) is a determining parameter during the industrial adjustment of boiler equipment [15].

Due to the use of the data of the paper [16] and the results of the industrial implementation of JNT burners, the emission parameters of modernized equipment are given in Table 1.

Table 1. Emission indicators of boiler equipment of small and medium productivity [17]

Boiler type	Heat capacity, MW	α_{cr}	NOx^{max}			NOx^{norm}		NO_x^{norm}/NO_x^{max}
			Measurements	Research scaled to α=1	Calculation	Research	Calculation	
NIISTU-5	0.5	1.45	130	69.89	73.50	66	61	0.95
KVN-2.9	2.9	1.20	80	66.67	133.31	88	101	1.32
DKVR-10	9.2	1.17	280	200.00	186.21	161	142	0.81
KVGM-20	23.2	1.14	295	268.18	234.19	194	171	0.72
PTVM-50	58.2	1.17	350	304.35	296.74	209	219	0.69

As can be seen from Fig. 2, there is a correlation of emission characteristics with the regime parameters of the equipment and its thermal load. Table 1 show that there is also a relation between the normalized and maximum concentrations of nitrogen oxides ($\overline{NO_x} = NO_x^{norm} / NO_x^{max}$). So, for boiler equipment with heat output from 6.5 to 50 GKal, $\overline{NO_x}$ ratio has a value in the range of 0.69–0.81, the exception is specific equipment represented by small-sized contact water heaters of KVN type and converted solid fuel boilers of NIISTU type [13]. For comparison, according to experimental data of paper [17], technologies with flow swirl have an average value of 0.78 with a deviation from the average value for different types of boiler equipment of no more than 7%. It should be noted that the average value of the parameter $\overline{NO_x}$ for JNT is lower by 8% compared to vortex burners on the corresponding equipment, due to a more perfect process of mixture formation and combustion, which is confirmed by the results of gas analysis of combustion products. Thus, on the regimes corresponding to NO_x^{norm}, on the one hand, there is actually no chemical underburn due to maximum temperatures, which, on the other hand, increases the emission of nitrogen oxides [14]. From the given data it is also clear that there is a significant increase in nitrogen concentrations both maximum (NO_x^{max}), and normalized (NO_x^{norm}) with an increase in the heat output of boilers (D_0).

The effect of D_0 productivity on the emission of nitrogen oxides (at N=100% and the same values of the furnaces shielding degree, types of burners, and volumetric heat load of the furnace space) can be explained by the action of the scale effect. If we consider the achieved emission level of nitrogen oxides as a result of heat exchange by radiation from the torch to the shielded surfaces of the boiler ($Q_{rad}=q_{rad}\cdot F_{sh}$, where q_{rad} is the radiation heat flow, F_{sh} is the shielded surface of the boiler furnace), then the fate of this heat removal in relation to the heat release of the torch ($Q_{heat}=q_v\cdot V_f$, q_v is the volume thermal voltage of the furnace, V_f is the furnace volume) will be determined by the dimensions of the boiler. Since the scale of the linear size of the furnace can be taken equal to $L=V_f^{1/3}$, the ratio of heat flows will be simplified as follows: $Q_{rad}/Q_{heat}=F_{sh}/V_f\approx 1/L$. It can be assumed that the productivity of the boiler (at nominal load and q_v=const) is proportional to the furnace volume ($D_0\sim L^3$), then $Q_{rad}/Q_{heat}\sim D_0^{-1/3}$. The last ratio indicates a decrease in the share of heat removal from the torch with an increase in the boiler dimensions, as a result of which the effective temperature of the torch and the level of toxic nitrogen oxides emission increase.

The influence of boiler dimensions on the level of nitrogen oxide emissions is confirmed by generalizations in [18], where it is shown that $NO_x\sim d_{eq}^{0.8}$, where d_{eq} is the equivalent diameter of the combustion chamber. The above confirms the significant influence on the concentration of NO_x in combustion products not only of maximum temperatures, but also of its cooling rate $dT/d\tau$, which significantly depends on the dimensions of the furnace $\frac{dT}{d\tau} = f\left(\frac{H}{V}\right) = f(d_{eq})$ and decreases as its size increases.

It is convenient to predict the emission indicators of low-power boilers (D_0<10 GKal) on natural gas according to the following dependence:

$$NO_x^{max} = a \cdot D_0^n, \quad (1)$$

where coefficients a and n are chosen individually for a certain type of equipment.

In the case of emission determination by boiler equipment of medium performance (11<D_0<120 GKal), it is better to apply the dependence:

$$NO_x^{max} = a \cdot D_0^n \big/ \left(b + c \cdot D_0\right), \quad (2)$$

where a, b, c are empirical coefficients.

Thus, the calculated values of the maximum NO_x^{max} in the Table 1 are obtained by formula (1) at a=100, n=0.27 (for KVH-7.56/6.5 and DKVR-10 boilers); for the NIISTU-5 boiler, the coefficients are a=92, n=0.266; for contact water heater KVN-2.9 – a=50, n=0.27. For the studied boilers of higher power (KVGM-20 and PTVM-50), the empirical coefficients are: a=1000, b=30, c=2.77.

To determine the normalized value of NO_x^{norm} concentrations, it is advisable to apply dependence (1), the values of the coefficients are as follows: a=76, n=0.27.

The results of the comparison of experimental and calculated values of characteristic concentrations of nitrogen oxides (Fig. 2 and Table 1) confirm a sufficient level of their coincidence. The deviations that occur in the obtained data can be explained not only by measurement errors, but also by a number of unaccounted factors, such as: the actual period of the object operation, features of the combustion chamber design. Thus, in practice, to determine the maximum value of NO_x concentrations, it is appropriate to use the dependence of the following form [14]:

$$NO_x^{max} = K_d \cdot K_D, \qquad (3)$$

where K_d is a discrete effects parameter, $K_D = a \cdot D_0^n$ is a performance parameter.

It should be added that the characteristics can be obtained in a similar way $NO_x^{max} = f(D_0)$ when burning other types of fuel.

If boiler performance D_0 when determining the impact on NO_x emission indicators is determined by the scale effect, then the load effect (N=(D/D_0)×100%) can be considered as a dependence of NO_x~$q_v^{0,5}$. If there is a correlation between the forcing of the furnace q_v and the load of the boiler, the corresponding emission characteristic is given in the form of a power dependence:

$$NO_x = a(N/100)^n = a \cdot (D/D_0)^n. \qquad (4)$$

According to the results given above, and taking into account the peculiarities of the application of formula (4), it can be stated that the coefficient a reflects the concentration level of nitrogen oxides at the nominal load of the boiler, taking into account the interaction of the excess air coefficient and other factors, the influence of which is purely discrete (type of burner, type of fuel, arrangement and number of activated burners, peculiarity of the combustion chamber design, etc.).

Fig. 3 shows the results of the adaptation of the natural gas combustion technology during the depletion of the exhaust air with combustion products on boilers with a capacity of 7.56 and 9.3 MW. Technologically, the scheme is a method of self-recycling and can be effectively implemented on the basis of JNT without technological limitations. Regulation of the volume of gases additionally supplied to the combustion chamber is carried out by a gate valve without the use of a recirculation pump. The introduction of the mixture is implemented through burners, the direct flow scheme of which, without swirling the fuel and oxidizer flows, ensures a sufficiently uniform concentration of the lean fuel mixture [19].

The amount of recirculation gases is determined by the ratio:

$$r = V_g / V_a, \qquad (5)$$

where V_g is the volume of recirculation gases, m^3/s; V_a is the volume of the air blower, m^3/s.

The concentration of oxygen in the air when recirculation gases are added can be estimated using the following relation:

$$C_{O_2} = \frac{0{,}209 \cdot \left[(1 + \alpha_f \cdot L_0) + (\alpha_f - 1) \cdot L_0 \cdot 0{,}01 \cdot r\right]}{(1 + \alpha_f \cdot L_0) \cdot (1 + 0{,}01 \cdot r)} \times 100, \qquad (6)$$

where α_f is the coefficient of excess air in the boiler furnace; L_0 is the stoichiometric coefficient [18]. When applying the given expression for the object under study, the concentration of oxygen in diluted air can be estimated with a relative error of no more than 2.0%.

When analyzing the results of ecological tests of boilers (Fig. 3), attention is drawn to the reduction of the impact of the unit load on C_{NOx} in the exhaust gases with an increase in the percentage of air dilution in the burners. This is especially evident for water heating boilers of the KV-G-6.5 type (Fig. 3, a).

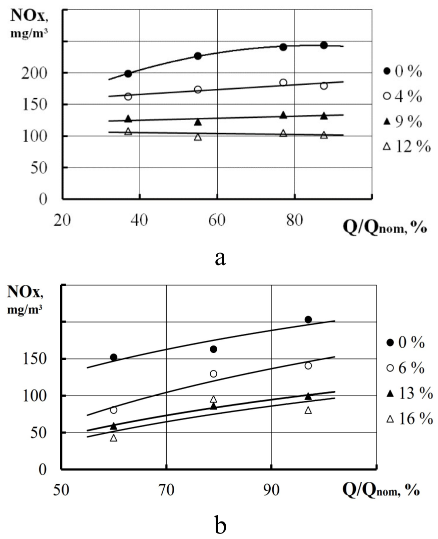


Fig. 3. Dependence of the concentration of nitrogen oxides on the heat load of the boilers and the percentage of recirculation gases into the furnace space:
a – KV-G-6.5; b –DKVR-10

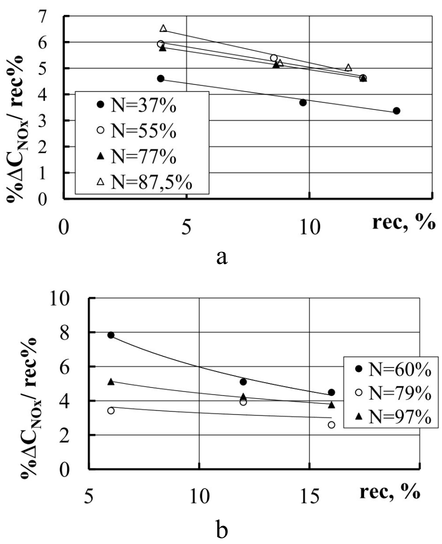


Fig. 4. The dependence of the decrease in the concentration of nitrogen oxides on the percentage of recirculation gases on the volume of ballast gases in the furnace space for boilers:
a – KV-G-6.5; b – DKVR-10

At that time, the specified feature was not typical for boilers of the DKVR-10 type (Fig. 3, b). Obviously, individual discrete effects are manifested, such as the specific heat stress of the furnace space, structural features of the gas path of the units, etc. Based on the above results, it can be stated that the introduction of 12–14% of combustion products into the combustion chamber of the boiler reduces the nitrogen oxide content in the combustion products by almost 2.5 times. At the studied objects, a reduction of emissions in the range of 2.8–7.8% was achieved for 1% of recirculation gases, the effect of suppressing the NO_x concentration decreases with an increase in the percentage of air dilution with gases (Fig. 4).

We consider it necessary to add that the introduction of combustion products in a volume of more than 12% significantly reduces the suppression of NO_x emissions (oxygen content in the exhaust air C_{O2}<19%, (Fig. 3, b)). In addition, an increase in the percentage of recirculation increases the emission of CO carbon monoxide (Fig. 5). As a result, a decrease in the total concentration of nitrogen oxides to 50–100 mg/m^3 was obtained (on individual DKVR-10 units, a decrease in concentrations below 50 mg/m^3 was achieved). It should be noted that even with maximum recirculation, the values of CO concentrations do not exceed the maximum permissible standards (C_{CO}<90 mg/m^3), and the high-quality installation of burners and the appropriate heat-technical adjustment of units based on the results of modernization when working without recirculation minimizes the concentration of carbon monoxide in waste gases as much as possible. In fact, JNT burners achieve 30% higher recirculation efficiency compared to vortex burners.

Obviously, the degree of homogenization of the fuel mixture is a determining factor in ensuring the effectiveness of technological denitrification. Thus, at the first stage of the process, the exhaust air is ballasted with waste gases, and at the second stage, fuel gas is mixed with ballasted air. Gradual preparation for combustion and high efficiency of mixture formation create the necessary conditions for the organization of effective micro-diffusion combustion of the fuel mixture, and oxygen depletion of the air is effectively regulated and limits the reverse process of chemical underburn formation. Thus, the limitation of the amount of recirculation gases may be due to individual features of the equipment in terms of reducing the efficiency of the method (Fig. 3) or over-time increase of C_{CO} (Fig. 5).

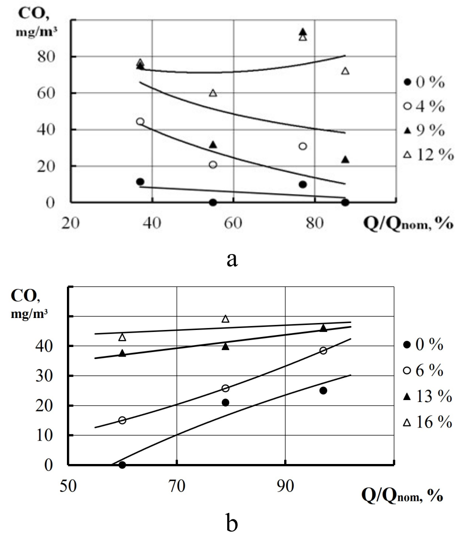


Fig. 5. Dependence of the concentration of carbon monoxide on the thermal load of boilers and the percentage of recirculation gases into the furnace space for boilers: a – KV-G-6.5; b – DKVR-10

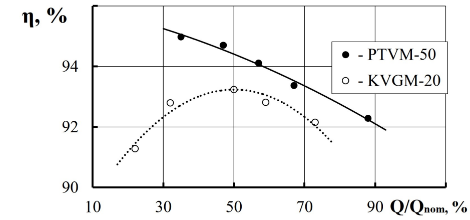


Fig. 6. Dependence of the efficiency of boiler units on the load when combustion products are introduced into the furnace space (self-recirculation scheme)

The paper evaluates the efficiency of boiler units (Fig. 6). The efficiency has a direct dependence on the load, and the most economical operation modes for both units are at partial loads. For KVGM-20, the characteristic has an extremum at approximately 50% of the nominal load, while for PTVM-50 it monotonically decreases as the power increases. It should be noted that the equipment operates at partial loads for more than half of the heating period, so the maximum efficiency and saving of energy resources will be obtained precisely in these modes. Although, considering the characteristics as a whole, it is possible to state a sufficiently high energy efficiency of the modernized fire equipment.

According to the results of statistical processing of the emission characteristics of boiler equipment modernized with JNT burners with a self-recirculation scheme, the decrease in the percentage of nitrogen oxides can be fairly accurately estimated by the dependence in the form:

$$\Delta C_{NO_x} = (a \cdot \ln(N\%) + b) \cdot (r_{rec},\%)^2 + c \cdot (N\%)^{0,4} (r_{rec},\%) + d \,, \qquad (7)$$

where the values of the equation coefficients are determined taking into account the boilers thermal engineering (Table 2).

It should be noted that for boilers of medium and high performance, due to the presence of various discrete influences, the aspect ratio is considered a convenient method for forecasting emissions:

$$\mathrm{NO_x} = \mathrm{NO_x^{max}} K_N K_\alpha = K_d K_D K_N K_\alpha \,. \quad (8)$$

For high-performance boilers, it is impossible to obtain emission characteristics in a "pure" form $NO_x=f(\alpha)$ and $NO_x=f(N)$ and in the form $NO_x=f(D_0)$ due to the existence of various influences (presence of recirculation, staged combustion, different layout and number of activated burners). To predict the emission characteristics of powerful boiler equipment, it is convenient to apply the method of influences compensation in the form:

Table 2. The coefficients value of the equation (7)

Boiler type	Thermal power, MW	The coefficients value			
		a	*b*	*c*	*d*
KVG-7.56/6.5	7.56	-0.048	0.070	1.15	0.4
DKVR-10	11.63	-0.043	0.040	1.04	2.0
KVGM-20	23.3	-0.035	0.077	1.01	2.8
PTVM-50	58.15	-0.055	0.054	1.13	3.3

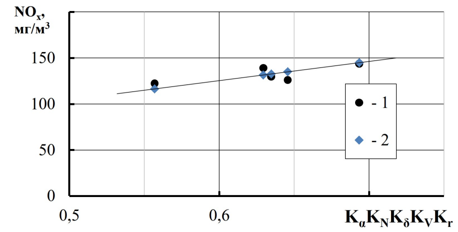


Fig. 7. Graphical interpretation of the method of influences compensation in the generalization of the emission characteristics of the PTVM-50:
1 – measurement; 2 – calculation

$$\mathrm{NO_x} = \mathrm{NO_x^{norm}} \prod_{i=1}^{n} K_i \,, \quad (9)$$

where K_i is the corresponding parameter of influence on the emission of nitrogen oxides.

Thus, for the PTVM-50 boiler, the following influence factors on emission indicators are: $K_\alpha=\alpha^{3.8}$; $K_N=(D/D_0)^{0.79}$; $K_\delta = \exp[-0.257\Delta\bar{h}_\delta]$, where $\Delta\bar{h}_\delta$ is the relative air supply, bypassing the burners (not applicable for JNT); $K_{\Delta V} = \exp[-0.2\Delta\bar{V}]$, where $\Delta\bar{V}$ is the specific distribution of gas on the tiers (is considered uniform for JNT); $K_r = \exp[-0.05r]$, where r is the degree of recirculation in %. The results of the proposed coefficients presentation, taking into account the normalized value NO_x^{norm}, are shown in Fig. 7.

Data given in Fig. 7 make it possible to state that a convenient method of conducting an objective assessment of the effectiveness of primary or secondary measures to reduce the emission of toxic nitrogen oxides has been chosen.

Conclusions

Based on the developments of National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", a universal technology of fuel burning, which is characterized by high efficiency in the organization of the technical combustion process, was created. As of today, modernization of a wide range of gas-consuming equipment, such as boilers, furnaces, dryers, metallurgical facilities, etc., has been carried out. Along with energy efficiency, the requirements for ensuring the environmental performance of modernized fire engineering equipment come to the fore. As a result of the wide implementation of the researched technology in the industry, it was found that there is an opportunity to ensure the reduction of nitrogen oxides by primary technological methods. It was stated that the simplest and most effective of them should be the introduction of recirculation gases into the furnace space.

It was established that the efficiency of the introduction of recirculation gases depends on the power of the unit and on their total volume when ballasting the oxidizer. The percentage reduction of nitrogen oxides by one percent of recirculation gases is C_{NOx}=2–8%, depending on the type of boiler unit and the above-mentioned conditions. Moreover, the highest efficiency of the process is achieved at partial loads when ballasting the air with gases by no more than 5–7% by volume. It was found that for boilers with a thermal capacity of up to 10 MW, the introduction of ballast gases by more than 12–14% significantly reduces the efficiency of the denitrification process. The developed recirculation scheme is implemented in water heating boilers with a capacity of 0.5–56 MW and DKVR-10 steam boilers (steam productivity of 10 t/h) based on jet-niche technology. As practice shows, its use makes it possible to increase the efficiency by 1/3 compared to vortex combustion technologies due to the rational distribution of fuel in the oxidizer volume. The actual concentration of nitrogen oxides does not exceed 100 mg/m^3 for all the above models of boilers, except PTVM-100, where the levels are slightly higher – 145 mg/m^3.

The analysis of the obtained results of the industrial implementation of burners shows that the local emission characteristics in the form of dependences of NO_x on operational factors have a purely individual character, i.e. reflect a different degree of influence on the level of nitrogen oxide emissions, are determined by the corresponding indicator $K_i=\varphi(f_i)$ and are of continuous nature.

In addition to the effects on the nitrogen oxides emission, which are of a continuous nature, there are also discrete effects, such as: the boiler type and the furnace design, the fuel type, the method of liquid fuel spraying, the layout of the burners in the furnace, etc., the cumulative parameter of the influence of which can be both more and less than 1.0.

Given the fact that the expected value of the oxidant excess in the furnaces of power boilers is close to α_{cr}=1.15–1.17 (to which the oxygen concentration in the waste gases corresponds to O_2=3%), it is advisable to carry out the reduction of the measured concentrations of nitrogen oxides in the waste gases of power boilers to the specified conditions.

When starting up energy boilers after installation or repair, it is appropriate to carry out the procedure of building a generalized environmental characteristic of the dependence form (8), on the basis of which it is possible to estimate the normalized concentration of nitrogen oxides NO_x^{norm}, which is an objective criterion of the level of environmental safety of a fire engineering facility.

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Енергоекологічна оцінка котельного устаткування, модернізованого на базі струменево-нішевої технології

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У статті наведено результати енергоекологічної оцінки котельного устаткування промислового призначення, обладнаного струменево-нішевою технологією спалювання. Наголошено, що до основних принципів, покладених в основу даної технології, відносять такі, як: раціональний розподіл палива в потоці окисника; стійка регульована структура течії палива, окисника і продуктів згоряння; саморегульованість складу паливної суміші в зоні стабілізації факелу при зміні навантаження агрегату. Підкреслено, що станом на сьогодні за допомогою струменево-нішевої технології модернізовано велику кількість промислового газоспалюючого устаткування, як-от: котли, печі, сушарки, об'єкти металургії та ін. Констатовано, що результати промислового впровадження технології дозволили накопичити значний обсяг технічної інформації й дали можливість зробити попередню екологічну оцінку при проведенні модернізації газоспалюючого устаткування. Як показує практика, на сучасному етапі основним напрямом вдосконалення технології є поліпшення її екологічних показників. У роботі встановлено вплив основних режимних і технічних параметрів вогнетехнічного обладнання на його емісійні показники. Доведено, що існує можливості зниження оксидів азоту первинними технологічними методами, найпростішим й найефективнішим з яких вважається введення газів рециркуляції у топковий простір. За результатами аналізу емісійних показників модернізованого вогнетехнічного обладнання потужністю 0,5–60 МВт отримано дані для оцінки емісійних показників котлів малої та середньої потужності залежно від основних впливових факторів, а саме: від типорозміру агрегату, коефіцієнта надлишку повітря й навантаження котла, а також враховано вплив введення газів рециркуляції у топковий простір на рівень концентрації оксидів азоту. Підтверджено ефективність застосування схеми введення газів рециркуляції в потік первинного повітря і переваги в порівнянні з технологіями спалювання на базі вихрових пальників. За результатами промислового експерименту встановлено енергетичну ефективність запропонованих заходів на прикладі залежностей ККД від навантаження котлів ПТВМ-50 і КВГМ-20.

***Ключові слова**: струменево-нішева технологія, оксиди азоту, режимні параметри, рециркуляція газів.*

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