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Boilers modernization due to energy-ecological improvement technology of burning

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According to the practice of burning gaseous fuels in energetic and industrial installations, one of the most important elements of the boiler-furnace process is the burner device (BD). The main processes taking place in a BD are hydrodynamic phenomena in the working channel that determine the efficiency of burning organic fuels due to such working stages: mixing fuel and oxidizer, ignition, stabilization of ignition torch and fuel burn up. These processes based on the phenomenon of heat and mass transfer and chemical interaction of burning components determine the ecological impact of the studied processes.

This paper is devoted to the energy-ecological evaluation of industrial-scale plants equipped with Jet-niche technology of burning (JNT). Today modernized are dozens of gas burning objects such as: steam and water boilers, industrial furnaces, dryers and heaters of steal ladles in metallurgy, cement mills and melting furnaces in industry. The main issue is to determine the influence of vitiated air to the emission characteristics of gas-powered equipment in a wide capacity range. At the nominal operating conditions a 2.5 fold reduction of nitrogen oxide concentrations up to 25...35 ppm was achieved at 12% volumetric gas recirculation. Thus, a reduction of NO_x emissions in the range of 3.4-4.8% per 1% of the recirculation gases was achieved. The effect was increased with the power set. The results are presented for steam water boiler units with a capacity of 6.5-50 gcal.

Keywords: jet-niche technology, gaseous fuel, hot-water boiler, nitrogen oxides

INTRODUCTION

Diatomic molecular nitrogen (N_2) is a relatively inert gas that makes up about 79% of the ambient air we breathe. The chemical element nitrogen (N), as a single atom, can be reactive and have different ionization levels from one to five. Thus, nitrogen can form several different oxides. In general, nitrogen oxides (NO_x) are a family of seven compounds. Nitrogen oxides take second place after sulfur dioxide among the elements that increase acid precipitation. Nitrogen oxides also impair visibility and play a significant role in the formation of photochemical smog [1].

It is known that there are different mechanisms of formation of nitrogen oxides during fuel combustion: thermal, fuel and fast. The proportion of fast nitrogen oxides is negligible and increases for fuel with a higher molecular weight. The proportion of thermal nitrogen oxides decreases. The content of thermal nitrogen oxides in gaseous fuels reaches more than 80% of the total emissions.

The nature of NO_x formation has not been thoroughly studied, the behavior of oxides is often ambiguous and theoretically unpredictable. The basis of NO_x are thermal oxides of nitrogen.

Reduction in the intensity of NO_x emissions can be achieved in two ways. The first one is associated with the direct improvement of the combustion process (so-called technological methods), and the second is achieved by purification of exhaust gases.

LITERATURE REVIEW

There are many technological factors that affect the level of nitrogen oxides emissions in a gas burning unit., such as the level of excess air, current load of unit, flue gas recirculation, afterburning, water or steam supply to the combustion zone, redistribution of fuel and air through the burner channels, redistribution of fuel and air on the burner tiers, switching off part of the burners, regulation of the intensity of swirling (for swirling type burning devices (BD)), use of a micro torch combustion mechanism (multi burner furnaces of power boilers and combustion chambers gas-turbine units) [2-10].

Application of catalytic combustion technologies belongs to the second method of denitrification of flue gases. It is divided into selective catalytic and selective non-catalytic removal of nitrogen oxides [11-13].

The efficiency of reducing emissions depends on the technology of fuel combustion. The base canonical principles of NO_x minimization are: preliminary mixture formation, stage combustion and direct-flow aerodynamic scheme of oxidant flow. The Jet-niche combustion technology (JNT) meets all the canonical principles [14]. The main features of the technology are as follows: rational distribution of fuel in the oxidant stream; stable

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regulated structure of fuel, oxidant and combustion products; self-regulation of the fuel mixture in the flame stabilization zone. The main element of JNT burners is a jet-niche system (Fig. 1) [15].

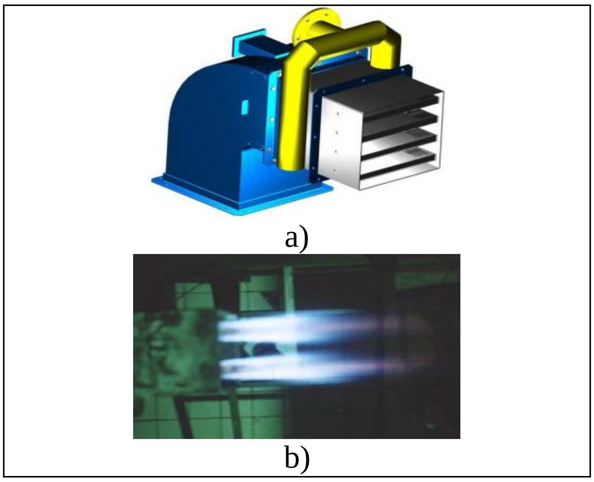

Fig. 1. Jet-niche fuel combustion technology: burner (a), open gas torch (b),

A significant experience of energy-ecological modernization of boiler equipment with a capacity of 0.5…125 MW has been gained on the basis of JNT.

The "National Emissions Reduction Plan for Large Combustion Plants" is valid in Ukraine [16]. The plan is designed for gradual implementation until 2032 inclusive. According to the plan, the implementation of primary technological measures is considered on the first stage, and the technologies based on the process of deoxidation of nitrogen oxides – on the second stage.

In particular, the aim of this research is defining the role of primary technological methods of nitrogen oxides reduction on boilers equipped with JNT type BD.

RESULTS AND DISCUSSION

The emission performance of boiler equipment is significantly influenced by the main process variables: the excess air factor in the unit furnace (α_f) and the productivity of the boiler (D_0) (Fig. 2).

The normalized indicators of nitrogen oxides NO_x^{norm} are practically important for the process of forecasting emission characteristics. They are determined in the absence of main operational influences at $\alpha_f = 1.0$. The maximum value of the nitric oxide concentration NO_x^{max} is reached at certain values of the critical excess air $\alpha_{cr} = \alpha_f$.

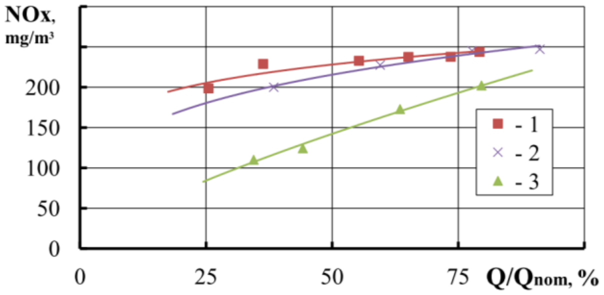

Fig. 2. Dependence of nitrogen oxides concentration on the main technological parameters on a boiler equipment with JNT: 1 – KVGM-20, 2 – KVG-7.56, 3 – TVG-8

The value of the critical excess air factor $\alpha_{cr1}>$ 1.0 (hereinafter α_{cr}) is a determining parameter during the industrial adjustment of boiler equipment. In fact, a further reduction of excess air on the burners in the direction of $\alpha \rightarrow 1.0$ leads to a decrease in the concentration of nitrogen oxides at simultaneously with an excessive increase in chemical fuel underburning. There is a second critical point of ecological indicators α_{cr2} ($\alpha_{cr2} > \alpha_{cr2}$). It corresponds to the minimum concentrations of carbon monoxide and is closer to the stoichiometric mixture implemented in burners [17].

Using the data of [17] and the results of industrial implementation of JNT, the emission parameters of the modernized equipment are presented in the Table below.

The parameter α_{cr} takes a fairly wide range of values 1.14-1.45, which is explained by the peculiarities of the studied equipment and its actual condition at the time of modernization. For instance, this parameter is close to 1.5 for boilers converted from solid fuel combustion to natural gas (NIISTU-5), but it is in the range of values α_{cr} = 1.14-1.2 for gas-fired boilers. The difference is determined by the peculiarities of the process of heat removal from the torch in the furnace space and the quantity of the air inflow. Intensification of these processes leads to an increase in the parameter α_{cr}. The reverse trend of the α_{cr} displacement closer to stoichiometry is related to the improval of mixing processes in the burners of boiler equipment. The results show the correlation between normalized and maximum concentrations of nitrogen oxides ($\overline{NO}_x = NO_x^{norm} / NO_x^{max}$). Thus, for boiler equipment with a heat power from 6.5 to 50 Gcal, the ratio is in the range of 0.63-0.81, the exception is a specific equipment, represented by small-sized water heaters of the contact type KVN and converted solid fuel boilers NIISTU.

Table. Emission indicators of low and medium capacity boiler units at rated load (N = 100%), degree of furnace waterwall (ψ = 0.55-0.8), and volumetric heat load of units q_v = 0.3-0.35 MW/m^3 (KVN-2.9 – q_v = 3.0 MW/m^3).

Boiler type	Thermal power,	α_{cr}	NOx^{max}			NOx^{norm}		
			Measured value	experiment is reduced	Calculation	Experiment	Calculation	NO_x^{norm}/NO_x^{max}
NIISTU-5	0.5	1.45	130	69.89	73.50	66	61	0.95
KVN-2.9	2.9	1.2	*80*	66.67	*133.3*	88	*101*	1.32
KVG-7.56/6.5	7.56	1.15	250	178.6	172.7	112	131	0.63
DKVR-10	9.2	1.17	280	200.0	186.2	161	142	0.81
KVGM-20	23.2	1.14	295	268.2	234.2	194	171	0.72
PTVM-50	58.2	1.17	350	304.4	296.7	209	219	0.69

For comparison, the technologies with swirling-type burners according to the experimental data of [17] have an average value of 0.78 with a deviation from the average value for different types of boiler equipment not more than 7%. The average value of the parameter for JNT is lower by 8% compared to swirling-type burners, due to a more advanced process of mixing and combustion, which is confirmed by the results of gas analysis of combustion products. As a result, there is no chemical underburning in the regimes corresponding to NO_x^{norm} due to higher levels of maximum temperatures, which in turn increases the emission of nitrogen oxides. The NO_x concentrations increase with increasing heat output of boilers (D_0).

If we take the achieved level of nitrogen oxide emissions as a result of heat transfer by radiation from the torch to the waterwall tubes of the boiler ($Q_{rad} = q_{rad} \cdot F_{tub}$, where q_{rad} is the radiative heat flux, F_{tub} is the waterwall surface of the boiler furnace) the part of this heat-sink in relation to the heat-sink of the torch ($Q_{heat} = q_v \cdot V_f$, q_v – furnace volumetric heat load, V_f –furnace volume), will be determined by the dimensions of the boiler.

The scale of the linear size of the furnace can be taken equal to $L = V_f^{1/3}$, then the ratio of heat fluxes will be simplified as follows: $Q_{rad}/Q_{heat} = F_{tub}/V_f \approx 1/L$. It can be assumed that the productivity of the boiler is proportional to the furnace volume ($D_0 \sim L^3$), then ($D_0 \sim L^3$), $Q_{rad}/Q_{heat} \sim D_0^{-1/3}$. As a result, there is a decrease in the flux of heat-sink from the torch with increasing dimensions of the boiler. Thus, the effective temperature of the torch increases and the levels of emissions of toxic nitrogen oxides rise too.

Forecasting of the emission properties for low power boilers (D_0<10 Gcal) can be done by the equation:

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

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

Forecasting of the emission properties for mean power boilers (11<D_0<120 Gcal) is convenient to execute by equation:

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

where: a, b, c – empirical coefficients.

Thus, the calculated values of the maximum NO_x^{max} in Table 1 were obtained by equation (1) at: $a = 100$, $n = 0.27$ (for boilers KVG-7.56/6.5 and DKVR-10); $a = 92$, $n = 0.266$ (NIISTU-5); $a = 50$, $n = 0.27$ (KVN-2.9); $a = 1000$, $b = 30$; $c = 2.77$ (KVGM-20 and PTVM-50).

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

The comparison of experimental and calculated values (Table 1) confirms a sufficient level of their coincidence. The data deviations can be explained by measurement errors and also by a number of unaccounted factors, such as: the life cycle of the facility, the design features of the combustion chamber, etc. The following formula is usable for determining the maximum value of NO_x concentrations on practice:

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

where K_d is the discrete influence parameter, $K_D = a \cdot D_0^n$ – productivity parameter.

It is possible to get the characteristics of combustion solid and liquid fuels in a similar way. If the boiler productivity D_0 is determined by the scale effect, then the influence of the load ($N = (D/D_0) \cdot 100\%$) can be considered as the $NO_x \sim q_v^{0,5}$. In case if there is a correlation between the forcing of the furnace q_v and the boiler load, the corresponding emission characteristic is represented as a power dependence of the form:

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

The coefficient a reflects the level of nitrogen oxides concentration at a nominal boiler load, taking into account the interaction of excess air factor and other discrete factors (burner type, fuel type, layout and number of switched burners, combustion chamber design features, etc.).

The results of technology implementation for natural gas combustion during depletion of air by combustion products on a boiler 9.2 MW are shown in fig. 3. The scheme is a self-recirculation and implemented on the water boilers with JNT burners type. 12-14% introduction of exhaust gases in the furnace space with blasting air reducing the content of nitric oxide in the combustion products almost 2.5 times. The emission reduction was achieved in the range of 2.8… 7.8% per 1% of recirculation gases.

The effect of suppression of NO_x concentration decreases due to increasing percentage of dilution of air with gases (Fig. 4).

The vitiated air with combustion products in a volume of more than 12% significantly reduces the suppression of NO_x emissions (oxygen content in the blast air less then 19%). In addition, increasing the percentage of recycling increases the emission of carbon monoxide CO (fig. 5).

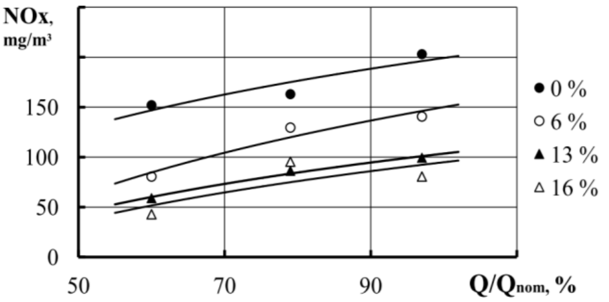

Fig. 3. Influence of boiler heat load and volume of recirculation gases for boiler DKVR-10 on NO_x concentration.

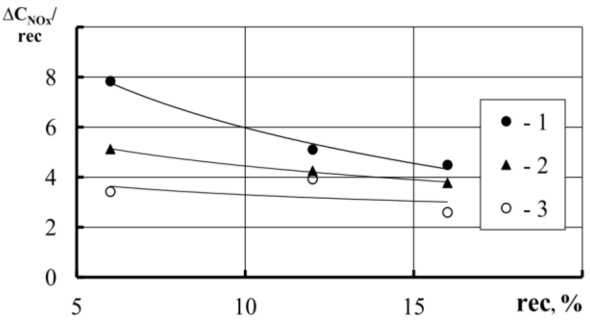

Fig. 4. Dependence of the nitrogen oxides concentration reduction on the volume of recirculation gases for boiler DKVR-10 when the heat load changes: 1 – N=60%, 2 – N=97%, 3 – N=79%.

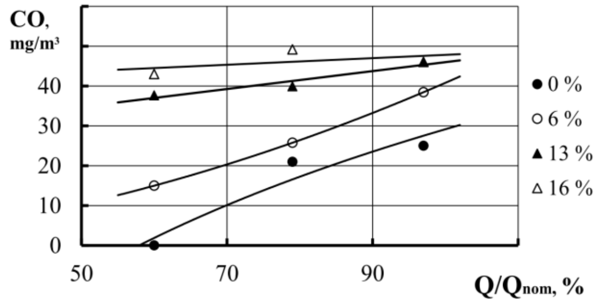

Fig. 5. Influence of boiler heat load and volume of recirculation gases for boiler DKVR-10 on carbon monoxide CO concentration.

The total NO_x concentration was reduced to 50…100 mg/m^3 (on some type units DKVR-10 a decrease in concentrations below 50 mg/m^3 was achieved). According to the gas analysis results, the maximum volume of recirculation gases do not lead to exceed the maximum allowable norms of carbon monoxide (C_{CO} <90 mg/m^3).

The stage of preparation for combustion and the high efficiency of mixture formation create the necessary conditions for the organization of efficient microdiffusion combustion of the fuel mixture. The process of oxygen depletion of air is effectively regulated and limits the chemical underburning. The main factor is the high quality of the fuel mixture homogenization. The process of mixture preparing consist of two consistent stages. The blast air is ballasted with exhaust gases in the first stage and then gaseous fuel is mixed with the vitiated air in the second stage. Thus, unexcessive increase in C_{CO} or specific equipment features in terms of reducing the efficiency are limiting factors of volume of recirculation gases.

The boiler efficiency is directly dependent of the load. The most economical modes of operation for both units are at partial loads (Fig. 6).

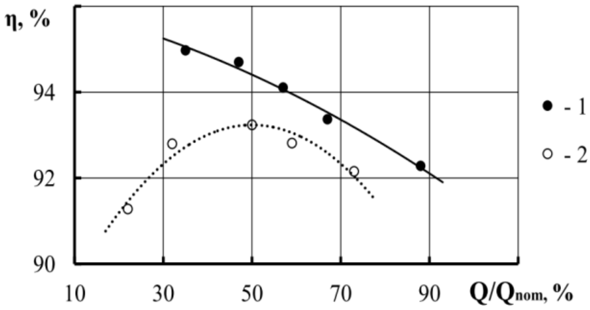

Fig. 6. Influence of boiler heat load on the efficiency of boiler units with exhaust gas recirculation for boilers: 1 – PTVM-50, 2 – KVGM-20.

The KVGM-20 characteristic has an extremum approximately on 50% of nominal loading whereas PTVM-50 characteristic monotonically decreases simultaneously with power increase. The maximum efficiency will be obtained in partial modes. It should be noted that equipment operates on the lowered loads on the main part of the heating period. Reliable forecasting method of NO_x emissions for medium and high capacity boilers due to the presence of various discrete effects is considered the ratio of the form:

$$NO_x = NO_x^{\max} K_N K_\alpha = K_d K_D K_N K_\alpha \qquad (5)$$

It is hard to obtain emission characteristics in "pure" form for high-performance boilers due to the existence of different influences (recirculation, staged combustion, different layout and number of switched-on burners). For predicting the emission characteristics of a powerful boiler equipment, it is convenient to use the method of influences compensation in the form:

$$NO_\text{x} = NO_\text{x}^\text{norm} \prod_{i=1}^{n} K_i , \qquad (6)$$

where K_i – corresponding emission parameter of nitrogen oxides impact.

For the PTVM-50 boiler as influential factors on the emission indicators are considered the following:

$K_\alpha = \alpha^{5,5}; K_N = \left(D/D_0\right)^{1,15}; K_\delta = \exp[-0,257\Delta\bar{h}_\delta]$, where $\Delta\bar{h}_\delta$ – relative air supply bypassing the burners (does not apply to JNT burners); $K_{\Delta V} = \exp[-0,2\Delta\bar{V}]$, $\Delta\bar{V}$ – specific distribution of gas in tiers (evenly for JNT burners); $K_r = \exp[-0,05r]$, де r – degree of recirculation, %. Proposed coefficients taking into account the normalized value NO_x^norm are shown in Fig. 7

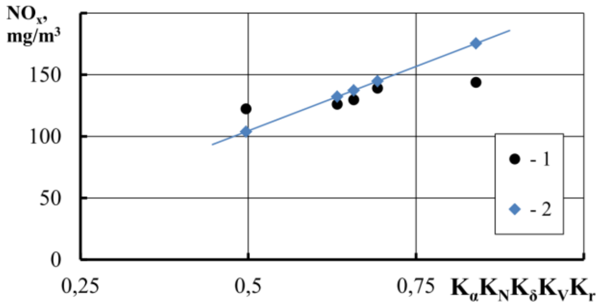

Fig. 7. Graphic interpretation of the influence of the compensation method for the PTVM-50 boiler – 1, prediction – 2.

CONCLUSIONS

1. The versatile high-efficiency technology of fuel combustion was widely introduced. Today, a wide range of gas-consuming energy equipments has been modernized, including: boilers, furnaces, dryers, metallurgical facilities, etc. The possibilities of nitrogen oxides reduction by primary technological methods were identified. The first necessary step in the implementation of environmental standards is the recycling of combustion products into the furnace volume.

2. Efficiency of nitrogen oxides reduction by flue gases depends on the current power of the unit and the amount of ballasting oxidant. The percentage reduction of nitrogen oxides by one percent of recirculation gases is the value of C_{NOx} = 2…8%. The greatest value was achieved at partial loads when ballasting the air with gases by no more than 5-7% by volume. The introduction of ballast gases more than 12…14% significantly reduces the efficiency of the denitrification process for boilers with a thermal capacity less than 10 MW. The recirculation scheme was implemented on hot water boilers with a capacity of 0.5-56 MW on the basis of jet-niche technology. JNT shows by 1/3 higher efficiency of the recirculation scheme compared to swirling-type combustion systems due

to high-quality mixing processes. The actual concentration of nitrogen oxides does not exceed 100 mg/m^3 (except for boiler PTVM -100).

3. Local emission characteristics of NO_x dependences on operational factors are purely individual. Characteristics are continuous and are determined by the indicator $K_i = \varphi(f_i)$. The influences compensation method can serve as a reliable tool for assessing the ecological performance in case of the presence of a sufficient amount of experimental data on the heat engineering setup of boiler equipment.

4. There are also discrete influences such as: type of boiler, design of furnace, type of fuel, layout of burners in the furnace, etc. The total parameter of influence could be more or less than 1.0.

5. The procedure of constructing a generalized ecological characteristic should be done by dependence (6). The normalized concentration of nitrogen oxides NO_x^{norm} is an objective criterion of ecological safety.

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