Efficient use of Steam Injection for Suppression of NO_X Emission in Gas-Turbines Engines

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Abstract: The article is devoted to the water steam injection use efficiency for the purpose of NO_x emissions suppression in gasturbine units. There was described the problem of saving the maximum allowable concentration of nitrogen oxides in the near-ground layer the alternative decision for what was the reduction of nitrogen monoxide concentration. As the result of tests there was confirmed the high efficiency of suppression of NO_x emission by steam. On the basis of the received results there was made a conclusion concerning the occurrence of necessary preconditions for the review of the role of steam in the technology of NO_x . emission wet suppression.

Keywords: Water steam injection, NO_X, emission suppression, gas-turbine units, reduction of nitrogen monoxide concentration.

1. Introduction

The realia of modern world power-generating necessitate the introduction of gas-turbine and vapor-gas units (GT unit and CCGT unit) that is one of the perspective trends of the further improvement of fuel-and-power sector. On the current stage, the power-generating GT unit and CCGT unit work mainly on natural gases, not containing sulphurs and other harmful admixtures. It has been established that when functioning at the GT unit full load the exhaust gases from such fuel combustion don't contain other emissions except the toxic nitrogen oxides forming in the combustion chamber. The table 1 shows the maximum allowable concentration (mac) specified by sanitary-hygienic norms of their concentration values in the air of populated locations that characterize their toxicity degrees.

Table 1. The maximum allowable concentration (mac) in the air of populated locations that characterize their toxicity degrees (mg/m^3)

Emission	Max one-time dose	Average daily dose
NO	0,600	0,06
NO_2	0,085	0,04

The most toxic of all the nitrogen oxides is nitrogen dioxide. Analyzing the global contamination of atmosphere it's usually taken into account the sum of nitrogen oxides as in natural conditions NO oxidizes to NO_2 and NO is converted to NO_2

$$NO + NO_2 = NO_X$$

Thus the actual toxicity of the gases [6] is estimated by the formula

$$F_{NOx} = C_{NOx} / mac_{NOx}$$
$$NO_x = C_{NOx} / 0.085$$

where the NO_xconcentration in GT unit exhaust gases is usually reduced to 15% O₂.

		0	
	Combustion	Intensity of	NO_X
GT unit type	products	emission, NO_X ,	concentration
	discharge, m ³ /s	g/s	mg/m ³
GT-700-5	35,4	6,89	200
GTK-5	35,4	6,89	200
GT-6-750	37,1	3,57	100
GTN-6	37,1	3,57	100
GT-750-6	45,6	15,5	350
GPA-Ц-6,3	47,1	3,04	70
GPU-6	23,3	2,41	109
GPA-Ц-8	47,8	4,83	110
GPU-10	68,1	4,3	70
GTN-10И	40,6	7,68	20
GTNP-10	66,6	11,7	180
GTK-16	79,2	7,57	100
GTN-16	67,4	11,6	180
GTN-16M-1	66,6	6,88	108
GPA-Ц-16	80,5	7,73	100
GPU-16	76,2	6,4	88
GTN-25	117,3	13,4	120

The real composition of nitrogen oxides, entering the nearground layer of the atmosphere (at the human respiration level), and their actual toxicity can differ since they depend upon processes, accompanying the diffusion of the exhaust gases tail in the atmosphere, and internal chamber processes, as well as upon the method of suppression of NO_xemission, implemented in GT unit. There is a possibility of the formation of a certain amount of NO₂ in the pre-flame zone of the combustion chamber [5, 11], but it's usually inconsiderable, especially taking into account the fact that its bigger part decomposes in flame [5]:

$$NO_2 + O \rightarrow NO + O_2$$

Due to this the composition of nitrogen oxides, exiting the combustion chamber and GT unit, is defined basically by the process of post-flame thermal oxidation of the air nitrogen.

The model of this process was described by Zel'dovich [1]

Table 2: The v	alues of nitro	gen emissions	with the
combustion	products for	gas-turbine uni	ts [4]

$$O_{2} \rightarrow O + O$$
$$O + N_{2} \rightarrow NO + N$$
$$N + O_{2} \rightarrow NO + O$$
$$O + O \rightarrow O_{2}$$

The actual toxicity of gases for the nitrogen monoxide that was formed in the process of oxidation can be defined by the following relation

$$F_{\rm NO} = C_{\rm NO}/\rm{mac}$$
$$NO = C_{\rm NO}/0,6$$

In the post-flame zone it's also possible formation of a certain amount of NO_2 . The most effective in this aspect is considered to be N0 oxidation by peroxide radical (HO₂) [6], as follows:

$$NO + HO_2 \rightarrow NO_2 + OH$$

In this process the velocity of the oxidation is defined by the concentration of HO_2 .

Several reactions are known to generate HO_2 radical [2]. The main of them occur at comparatively low temperatures (less than 800-900 K [6]) and are realized according to the triple concussion scheme:

$$H + O_2 + M \rightarrow HO_2 + M$$

where M is any third molecule, the purpose of which is to energetically stabilize the radical [2].

As far as the temperatures, under which the oxidation of CH_4 takes place, are concerned, there is also certain probability of the following reaction:

$$CHO + O_2 \rightarrow CO + HO_2$$

According to the above-mentioned particularities of this process at full load modes of GT unit, the concentration of HO_2 in the combustion chamber and, consequently, the concentration of NO_2 on the output from it is usually small; the exhaust gases contain mainly NO. However, upon its exiting from the exhaust pipe, NO gradually oxidizes to NO_2 , influence by atmospheric ozone:

$$NO + O_3 \rightarrow NO_2 + O$$

Considering the expression NO_2/NO_X it can be noticed that in connection with the peculiarities of this process this ratio increases.

Consequently the total actual toxicity rate of nitrogen oxides emissions in the exhaust gases tail also begins to increase:

$$\begin{split} F_{\Sigma} = & F_{NO} + F_{NO2} \\ F_{\Sigma} = & C_{NO} / 0.6 + C_{NO2} / 0.085 \end{split}$$

To preserve the threshold concentration rate of nitrogen oxides in the near-surface level under such conditions is possible only by increasing the exhaust gases diffusion in the atmosphere by the means of increase the height of the smokestacks N, the cost of which in single-pipe variant is equal to [8]

$$K \approx H^{2,2}$$

Summing up the above-stated it's obvious that the underperforming measures require an alternative decision like the reduction of nitrogen monoxide output concentration. In accordance with mechanism of nitrogen monoxide formation [1], this can be furthered by reduction of the maximum temperature in the reaction area of the

combustion chamber and the time of reagent presence within the zone of these temperatures. At present, most methods of the reduction of nitrogen oxides emissions are realized by temperature values reduction [3, 7].

The authors have researched the impact of water steam (H_2O) injection into the combustion chamber on nitrogen oxides emission and composition.

This method differs by its constructive simplicity and is considered to be very efficient, in spite of its negative consequences. Consequently this method is used in GT unit and CCGT unit both as the target, so-called "ecological" steam injection, and as a component of the "energygenerating" injection (which serves the purpose of increasing of capacity and efficiency of CCGT unit - monarCCGT units of STIG type); as well as a reserve method for NO_X suppression, auxiliary to the main one.

Remember about the air temperature supplied into the combustion area as there is the dependence between the number of nitrogen oxide emissions and the air temperature in chamber (figure 1).



Figure 1: The influence of air temperature in combustion on nitrogen oxides formation [4]

The results of the test of model combustion chamber at vapor injection into the flow of initial air are shown in Figure 2 in the form of the following relations

$$NO_X = f(G_{H2O}/G_{fuel})$$

Where G – mass consumption;

 T_3 – temperature of the gases at output from the combustion chamber. $T_3 \approx 1150 K$



flow of primary air:

- a) the influence of relative emission supplied into the steam combustion chamber $G_{ste'}/G_{fuel}$ on the NO_X components at T_{cp} =1473 K;
- b)the dependence between the relative content of NO_2/NO_X from G_{ste}/G_{fuel} and T_{cp}

To receive the actual results there was made an imitate model of nominal state of GT unit operation with maximum NO_x concentration in a one-shaft GT unit design and with maximum NO_x concentrationand maximum mass gases emissions due to the maximum speed of turbine compressor (gas generator) in a two-shaft GT unit design. The results confirm the high efficiency of the suppression of NO_x emissions by the means of steam. E.g., at steam consumption rate 0.5, the consumption of NO_x fuel decreases from 98 to 55 mg/m³ i.e. in 1.8 time, whereas at steam consumption rate equal to fuel consumption it decreases in 3 times.

The figure 2 (*a*) illustrates the same results displaying the NO_X decomposition into its components: NO and NO_2 . It's obvious from the comparison between the curves the defining role of NO in NO_X concentration decrease at steam injection into the combustion chamber.

The concentration of NO₂ at steam injection, in spite of drastic reduction of NO concentrations, doesn't decrease but even somewhat increases. As a result, the steam injection into the combustion chamber is accompanied by a drastic increase of NO₂ i.e. NO₂/ NO_X relative content in the exhaust gases (figure 2, b).

This is possible only if the concentration of HO_2 radical at steam injection increases in the chamber. For it to be formed, along with the triple concussion also atomic hydrogen is needed. It is believed [6] that at combustion in normal atmosphere (without steam) the main source of the atomic hydrogen, required for this reaction, is carbon oxides burning-out reaction taking place at 900-1100 K:

$$CO + OH \rightarrow CO_2 + H$$

Probably, at steam (H₂O) injection into the combustion chamber to the atomic hydrogen, generated by the reaction, is added also the atomic hydrogen, forming at the process of thermal dissociation of the water steam injected into the camera, which begins at 875 K and rapidly progresses at further increase of the vapor heating temperature.

From the above-stated we can conclude that water steam injection into the combustion chamber influences upon nitrogen oxides emission not only by reduction of thermal level in the reaction area, but also by a direct impact on chemical processes, which results in a drastic increase of NO₂/NO_X correlation in the exhaust gases. This results, in its turn, in a similarly drastic change of the output (at exiting from smokestack) level of actual toxicity of emitted gases F_{Σ} in comparison with its estimation based on NO_X content, as well as a weak dependency of this toxicity upon steam concentration (Figure 3).

At parameters, typical for GT unit exhaust gases (R = 0.1 MPa, T = 773-873K), the average lifetime of peroxide radicals ~ 1 s [2].

Therefore at high velocities of the gas flow and short lengths exhaust tract in modern GT unit, a part of H_2O radicals can

be removed beyond the limits of combustion chamber and smokestack.



Figure 3: Actual toxicity of GT unit exhaust gases at steam injection into the combustion chamber: $1 - F_{NOX}$;

$$2 - F_{\Sigma} = F_{NO} + F_{NO}$$

A part of H_2O can also take part in oxidizing processes NO \rightarrow NO₂ along with atmospheric ozone, taking place in dissipating gas tail. All this provides a sufficient reason for revising the role of steam in NO_xemissions moisture suppression technologies, as well as putting certain corrections into development of exhaust systems and those designed for combustion products diffusion in the atmosphere, and programs of GT unit (CCGT unit) control, based on steam injection into the combustion chamber

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