**Environmental safety and toxicity indicators of gas  
and fuel oil boilers**

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**Abstract.** This article presents the results of a study on the impact of secondary and tertiary air proportions and their ratios on the formation of nitrogen oxides and carcinogenic PAHs during the combustion of gas and fuel oil. Indicators of total and partial toxicity of combustion products under various conditions of conventional and staged combustion of gas and fuel oil were determined, and a comprehensive analysis was performed. The research showed that the total toxicity of gas combustion decreased by 51%, while the toxicity of nitrogen oxides alone was reduced by approximately 59%. At the same time, the toxicity of soot increased by 1.8 times, and that of benzo(a)pyrene by about 2 times (due to their low initial concentrations), which led to a 10% increase in overall toxicity. Thus, it was concluded that the tested three-stage gas combustion regime can be recommended for use.

**INTRODUCTION**

The development of scientific foundations for in-furnace methods to reduce the toxicity of combustion products of gas and fuel oil has been carried out without consideration of the actual condition of the boiler, without optimizing fuel combustion modes, or improving the efficiency of the main equipment. Moreover, these studies have often been one-sided, based on traditionally declared components of incomplete combustion (usually CO) and nitrogen oxides. Meanwhile, emissions of another unregulated group of carcinogenic substances and soot — which increase several times during fuel oil combustion, and especially during its co-combustion with gas — have been unfairly neglected. Furthermore, even traditional methods of gas and fuel oil combustion are not sufficiently studied, although their toxicity in operating boilers significantly depends not only on the main parameters .characteristics of fuel-air mixture, design and operating parameters, but also on the elemental condition and wear of the equipment, poor adjustment of combustion modes, which can also influence the ratio of incomplete combustion components to NOx. This explains the significant variation in the effectiveness of in-furnace methods for reducing combustion toxicity reported in the literature [1-5].

The developed boiler retrofit schemes [1-3] made it possible to separately study the influence of the proportion of secondary and tertiary air and their ratio on the formation of nitrogen oxides and carcinogenic PAHs during the combustion of gas and fuel oil. Consequently, this allowed for a deeper understanding of the mechanisms of interdependence in the formation of emissions from various harmful substance groups, the formation of which depends on the excess air ratio in the combustion zone and other operating conditions, often in mutually opposite ways [4-6].

Boiler modernization projects for TGM-94 units at the Nevinnomysskaya GRES, the Krasnodar CHP plant, and TGM-104 boilers at the Mary GRES for staged combustion of gas and fuel oil were carried out by Kharkiv Central Design Bureau “Energoprogress” of LLC “Kotloturboprom” (Kharkiv, Ukraine) [1-3, 7-11].

Various burner configurations for TGM-94 gas-fuel oil boilers were tested, allowing air to be supplied in two-, three-, or four-stage modes (Fig.1), which led to a significant improvement in environmental performance and compliance with emission limits for controlled pollutants, while maintaining the same levels of uncontrolled sulfur oxide emissions. At the same time, high environmental, reliability, and techno-economic performance was ensured for the boiler during both separate and combined staged combustion of gas and fuel oil across the entire load range [5-7, 12-16].

|  |  |
| --- | --- |
|  |  |
| a) | b) |
|  |  |
|  |  |
| c) | d) |
| **FIGURE 1.** Modernization Schemes of TGM-94 Boilers: Unit №6 at Tashkent TPP (a), Units №8 and 11 at Nevinnomysskaya TPP (b), TGM-104 Unit №3 at Mary GRES (c), and TGM-94 Unit №9 at Krasnodar CHP (d) | |

The interrelation between the emissions of two antagonistic groups of harmful substances - NOx concentration, soot, and benzo(a)pyrene - was also traced using a unified methodology on operating boilers (for both conventional and unconventional methods), and a correlation between them was established [17-21].

These data, considered from the perspective of total and partial toxicity for each combustion mode, provide an objective environmental understanding of existing gas and fuel oil combustion regimes, and help guide the implementation of in-furnace measures. Indicators of total and partial toxicity of combustion products under various modes of conventional and staged combustion of gas and fuel oil were determined and comprehensively analyzed. The results of these studies are as follows (Table 1) [22-26]:

- The toxicity of natural gas combustion products during conventional single-stage combustion is determined by nitrogen oxides toxicity by 95.6-99.25%. The developed and tested three-stage gas combustion mode was superior to an unoptimized combustion mode in all environmental parameters, including a 28% reduction in total toxicity. Total toxicity decreased by 51%, and the toxicity of nitrogen oxides alone was reduced by approximately 59%. At the same time, the toxicity of soot increased 1.8 times, and benzo(a)pyrene about 2 times (due to their initially low concentrations), which led to a 10% increase in total toxicity. Thus, the tested three-stage gas combustion mode can be recommended for practical use;

**TABLE 1.** Environmental safety under various modes of gas and fuel oil combustion in TGM-94 boilers of different GRES, expressed through indicators of total and specific toxicity of combustion products

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Object of study (boiler type, number of burners per stage), type and method of fuel combustion | Main operational and environmental combustion parameters | | | | | | | | | Patents\*\*  № |
|  |  |  | , | Indicators of total and specific toxicity (in %) | | | | |
|  |  |  |  |  |
| 1. Navoi GRES (TGM-94, 21 TKZ burners on 3 stages), hydrogen sulfide-containing natural gas (): | | | | | | | | | | 1208412 |
| Single-stage combustion | 1,00 | 0 | 1,4 | 510 | 6276  (100%) | 220  (3,51%) | 6000  (95,6%) | 15\*  (0,24%) | 41  (0,65%) |
| Two-stage combustion | 0,82-0,89 | 0,22-0,36 | 1,4 | 255 | 3295  (100%) | 220  (6,7%) | 3000  (91,0%) | 19\*  (0,58%) | 56  (1,7%) |
| 2. Tashkent GRES (TGM-94, 21 TKZ burners on 3 stages), natural gas: | | | | | | | | | | 1346907 |
| Single-stage combustion | 1,00 | 0 | 1,4 | 608 | 7207  (100%) | 0 | 7153  (99,25%) | 12\*  (0,17%) | 42\*  (0,58%) |
| Two-stage combustion ("vertical") | 0,75 | 0,25 | 1,4 | 225 | 3087  (100%) | 0 | 3000  (97,2 %) | 20\*  (0,63%) | 67\*  (2,17%) |
| Two-stage combustion (“horizontally”) | 0,85 | 0,15 | 1,4 | 735 | 8707  (100%) | 0 | 8647  (99,3 %) | 13\*  (0,15%) | 43\*  (0,55%) |
| Three-stage combustion | 0,67-0,73 | 0,27-0,33 | 1,4 | 266 | 3193  (100%) | 0 | 3129  (98%) | 17\*  (0,5%) | 47\*  (1,5%) |
| 3. Nevinnomysskaya GRES (TGM-94, 6 HFTs burners in 2 tiers), Stavropol natural gas: | | | | | | | | | | 1346907 |
| Single-stage combustion | 1,0 | 0 | 1,4 | 364 | 4510  (100%) | - | 4282  (95,0%) | 18  (0,34%) | 210  (4,66%) |
| The same, unadjusted mode | 1,0 | 0 | 1,4 | 210 | 3078  (100%) | - | 2471  (80,3%) | 57  (1,8%) | 550  (17,9%) |
| Three-stage combustion | 0,69 | 0,31 | 1,4 | 150 | 2208  (100%) | - | 1765  (79,9%) | 33  (1,5%) | 410  (18,6%) |
| 4. Nevinnomysskaya GRES (TGM-94, 6 HFT burners in 2 tiers), high-sulfur fuel oil (): | | | | | | | | | | 1398553 |
| Single-stage combustion | 1,0 | 0 | 1,4 | 412 | 14501  (100%) | 8740  (60,3%) | 5304  (36,6%) | 327  (2,26%) | 130  (0,84%) |
| The same, unoptimized mode | 1,0 | 0 | 1,4 | 315 | 14263  (100%) | 8740  (61,3%) | 3706  (26,0%) | 1467  (10,3%) | 350  (2,4%) |
| Three-stage combustion | 0,78 | 0,22 | 1,4 | 231 | 12365  (100%) | 8740  (70,7%) | 2718  (22,0%) | 727  (5,9%) | 180  (1,4%) |
| 5. Nevinnomysskaya GRES (TGM-94, 6 HFT burners in 2 tiers), co-combustion of gas and high-sulfur fuel oil | | | | | | | | | | 1346907, 1398553 |
| Single-stage combustion | 1,0 | 0 | 1,4 | 350 | 8875  (100%) | 4370  (49,2%) | 4118  (46,4%) | 107  (1,25%) | 280  (3,15%) |
| The same, unadjusted mode | 1,0 | 0 | 1,4 | 262 | 11815  (100%) | 4370  (37,0%) | 3082  (26,1%) | 2333  (19,7%) | 2030  (17,2%) |
| Two-stage combustion (“vertically”) | 0,69 | 0,31 | 1,4 | 190 | 8162  (100%) | 4370  (53,5%) | 2235  (27,4%) | 107  (1,3%) | 1450  (17,8%) |
| Three-stage combustion | 0,69 | 0,31 | 1,4 | 196 | 7906  (100%) | 4370  (55,3%) | 2306  (29,2%) | 200  (2,5%) | 1030  (13,0%) |
| 6. Tashkent GRES (TGM-94, 21 TKZ burners on 3 tiers), sulfur-containing fuel oil (): | | | | | | | | | | 1346907, 1398553 |
| Single-stage combustion | 1,0 | 0 | 1,4 | 505 | 11824  (100%) | 5400  (45,7%) | 5941  (50,2%) | 333\*  (2,82%) | 150\*  (1,28%) |
| Three-stage combustion | 0,87-0,89 | 0,13 | 1,4 | 260 | 10310  (100%) | 5400  (57,5%) | 3060  (32,6%) | 733\*  (7,8%) | 200\*  (2,1%) |

- The total toxicity of combustion products from high-sulfur fuel oil is about 2.0-3.2 times higher than that of gas. The toxicity is distributed as follows: nitrogen oxides — 36.6%, sulfur oxides — 60.3%, soot — 2.26%, benzo(a)pyrene — 0.84%. Under unoptimized combustion conditions, the total toxicity remains at about the same level (within ~1%). However, the redistribution of toxicity changes as follows: a 30% reduction due to incomplete combustion is fully offset by an increase in soot toxicity by 4.5 times and benzo(a)pyrene by ~3 times, while the toxicity of uncontrolled sulfur oxides remains unchanged. Despite the impressive ~49% reduction in the partial toxicity of nitrogen oxides and the achievement of emission limit values (ELVs) through three-stage fuel oil combustion, the total toxicity compared to the optimized conventional combustion mode was reduced by only ~15%;

-The worst-case scenario occurs during co-combustion of gas and high-sulfur fuel oil: under optimized combustion modes with conventional single-stage combustion, the toxicity distribution is as follows: nitrogen oxides — 46.4%, sulfur oxides — 49.2%, soot — 1.25%, benzo(a)pyrene — 3.15%. Under unoptimized conditions with excess air coefficients of 1.06-1.08, total combustion toxicity increases by 33%. Here, a 25% reduction in toxicity due to incomplete combustion is more than offset (by 8%) by a 22-fold increase in soot toxicity and a ~7-fold increase in benzo(a)pyrene, while the toxicity of uncontrolled sulfur oxides remains unchanged. The three-stage gas and fuel oil combustion mode was superior to the unoptimized mode in all environmental parameters, including a 33.1% reduction in total toxicity, a 49.3% decrease in benzo(a)pyrene toxicity, and an 87% reduction in soot toxicity. However, compared to the optimized conventional fuel oil combustion mode, the total toxicity was reduced by only ~11%, although the partial toxicity of nitrogen oxides decreased by ~44%. Still, an increase in soot toxicity by 1.87 times and benzo(a)pyrene by ~3.68 times led to an increase in total toxicity by 13.9%.

The obtained experimental data allow for the application of correlation dependencies to other fuels and thermal power stations as well [27-36].

Of course, it is not possible to establish a correlation between the concentrations of antagonistic groups of toxic substances for the full range of equipment wear states and their associated unoptimized combustion modes of gas and fuel oil. However, the data obtained in this study are reliable within the limits of the achieved measurement accuracy [37-43].

In Kazakhstan, since July 1, 2008, newly constructed and reconstructed enterprises are subject to fairly strict specific emission standards for nitrogen oxides into the atmosphere. As shown by the studies conducted, it will be difficult to meet these standards using only in-furnace methods — even when burning an environmentally clean fuel like natural gas — without the development of a new generation of boilers. However, in practice, we are still unable to obtain the necessary funding to continue this line of work [41-45].

**CONCLUSION**

The developed boiler modernization schemes made it possible to separately study the influence of the proportion of secondary and tertiary air, as well as their ratio, on the formation of nitrogen oxides and carcinogenic PAHs during the combustion of gas and fuel oil. This, in turn, enabled a more comprehensive understanding of the mechanisms linking the formation of the experimental data obtained make it possible to apply correlation dependencies at thermal power plants (TPPs).

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