Numerical Research of Nitrogen Oxides Formation for Justification of Modernization of P-49 Nazarovsky State District Power Plant Boiler on the Low-temperature Swirl Technology of Burning

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Abstract. Compliance with increasingly stringent normative requirements to the level of pollutants emissions when using organic fuel in the energy sector as a main source of heat, demands constant improvement of the boiler and furnace equipment and the power equipment in general. The requirements of the current legislation in the field of environmental protection prescribe compliance with established emission standards for both new construction and the improvement of energy equipment. The paper presents the results of numerical research of low-temperature swirl burning in P-49 Nazarovsky state district power plant boiler. On the basis of modern approaches of the diffusion and kinetic theory of burning and the analysis physical and chemical processes of a fuel chemically connected energy transition in thermal, generation and transformation of gas pollutants, the technological method of nitrogen oxides decomposition on the surface of carbon particles with the formation of environmentally friendly carbonic acid and molecular nitrogen is considered during the work of low-temperature swirl furnace. With the use of the developed model, methodology and computer program, variant calculations of the combustion process were carried out and a quantitative estimate of the emission level of the nitrogen oxides of the boiler being modernized. The simulation results and the experimental data obtained during the commissioning and balance tests of the P-49 boiler with a new furnace are confirmed that the organization of swirl combustion has allowed to increase the efficiency of work, to reduce slagging, to significantly reduce nitrogen oxide emissions, to improve ignition and burnout of fuel.

1. Introduction
Combustion of fuel in chamber furnaces is followed by emissions in the atmosphere of gaseous pollutants – nitrogen oxides (NOₓ) and sulfur oxides (SOₓ) [1…3]. Today torch burning has the restrictions caused by the becoming tougher requirements to ecological indicators [4] and the lowered operational characteristics connected with slagging of heating surfaces and questions of explosion safety that demands further improvement of hydrocarbon fuels use processes [5, 6].

One of effective ways of power use of coals is the low-temperature swirl (LTS) technology of burning developed at the Leningrad polytechnic institute (now the St. Petersburg polytechnic university of Peter the Great) under the leadership of professor V.V. Pomerantsev [7]. In LTS fire...
chamber repeated forced circulation of a fuel of coarsened grinding in the conditions of step supply of an oxidizer is organized [8]. Such scheme allows to reduce temperature level in fire chamber (an average on 100…250 K) and to level the temperature field in furnace volume, to completely exclude uses of liquid fuel for torch illumination, and also to liquidate slagging of heating surfaces [9]. In the lower swirl zone of fire chamber there is an intensive decomposition of nitrogen oxides on surface of the burning coke particles [10…12], and repeated circulation of fuel and ash particles in combination with the lowered level of temperatures, leads to the binding of sulfur oxides with mineral part of a fuel [13], thereby the LTS burning can be referred to technological ways of decrease in emissions of harmful substances during the work of the boilers.

The considerable positive experience of implementation of LTS technology accumulated so far [14…16], has allowed to recommend it for the implementation on boiler of P-49 of the block of 500 MW of Nazarovsky state district power plant for the purpose of its technical and economic and ecological indicators improvement.

Need of ecological justification of the project has defined the work purpose – development of mathematical model and numerical research of generation and transformation of nitrogen oxides and sulfur in the course of low-temperature swirl combustion of a solid fuel in P-49 boiler with LTS fire chamber for decrease in their emissions.

2. Need for technical re-equipment of the P-49 boiler of Nazarovsky state district power plant

P-49 boiler (of $D_{pp} = 1600$ t/h, $p_{pp} = 25$ MPa, $t_{pp} = 818$ K) the No. 7 direct-flow, with liquid slag removal (settlement coefficient of slag catching – 0.4), with balanced traction, is designed to work in the block with the turbine K-500-240. The boiler consists of two housings with three-running configuration working independently from each other. The general view of boiler is shown in the figure 1.

![Figure 1. General view of boiler of P-49](image_url)
screen pipes) on 50mm. In the lower part of "cold" funnel pipes of the front and back screen have created the outfall for slag exit from fire chamber. In middle part of fire chamber of the panel of front wall of LRP form front aerodynamic ledge with a departure in fire chamber which is intended for formation of the swirl zone of a fire chamber. Lower forming ledge has inclination to the horizon 25°, upper – 50°. For decrease in the maximum temperatures and temperature at the exit from fire chamber in swirl zone 10 intra furnace screens are established [17].

The long operating experience on strongly slaging nazarovsky coals has shown that work of boiler of P-49 is characterized by the following shortcomings:

1. The maximum long load of boiler makes 75...80 % from nominal (1200...1280 t/h) on condition of slagging of the screen surfaces of heating located at the exit from fire chamber. High temperature of gases at the exit from a fire chamber is caused by the increased humidity of settlement fuel (dried) and unsatisfactory aerodynamics of the fire chamber and burners.

2. The actual gross efficiency of the boiler is at the level of 88...89 % with an estimated – 92 %. The main reason for low efficiency – high losses with the leaving gases (\(\text{w}_{\text{og}} = 473...493\) K, \(\alpha_{\text{og}} \approx 1.72\)).

3. The minimum load of boiler makes 550 t/h on condition of stable slag exit.

4. Emissions of nitrogen oxides exceed normative values and make 1000...1200 mg/nm³.

3. Model of a burning process in LTS fire chamber of Nazarovskoy state district power plant P-49 boiler

The model of furnace process is based on the diffusion and kinetic theory of burning, considers generation and transformation of nitrogen oxides when burning fuel, has possibility of change qualitative (type and composition of solid fuel, its grinding and so forth) and quantitative characteristics of process (fuel consumption, speeds of burners air, air of the lower and tertiary blasting and so forth), and allows to carry out quantitative estimates of gaseous pollutants emissions during the work of a boiler. Consideration of burning process from diffusion and kinetic positions [18], has allowed to make system of the nonlinear differential equations of diffusion and kinetics of type:

\[
dG_j = -(D/RT) \cdot (d^2 p_j / dx^2) dx ; \quad G_j = (\alpha_{j \rho} / RT) \cdot (p_j - p_{\rho}) ; \quad dG_j / d\tau = C_j \cdot k_j ,
\]

(1)

Taking into account oxidizing and recovery reactions of the particles going on surfaces, and the homogeneous reactions proceeding within interface:

\[
\begin{align*}
\text{heterogeneous} & \\
\text{at "dry" gasification} & \text{at "wet" gasification} \\
1. \quad C + O_2 = CO_2 + 394.6 & 3'. \quad C + H_2O = CO + H_2 - 130.4 \\
2. \quad 2C + O_2 = 2CO + 219.6 & 3'. \quad C + 2H_2O = CO_2 + 2H_2 - 132 \\
3. \quad C + CO_2 = 2CO - 175.6 & 3''. \quad C + 2H_2 = CH_4 - 74.8 \\
\text{homogeneous} & \\
4. \quad CO + O_2 = 2CO_2 + 570.2 & 4'. \quad 2H_2 + O_2 = 2H_2O + 231.5 \\
4'. \quad CH_4 + 2O_2 = CO_2 + 2H_2O + 891 & 4''. \quad CO + H_2O = CO_2 + H_2 + 40.4
\end{align*}
\]

(2)

Change of constants of speed of chemical reactions from temperature submits to Arrhenius's dependence:

\[
k_i = k_{0i} \cdot \exp[-E_i/(RT)] ,
\]

(3)

where \(k_0\) – preexponential multiplier of dependence of Arrhenius (in m/s for heterogeneous and in 1/s with for homogeneous reactions); \(E\) – the apparent energy of activation, J/mol.
For calculation of communication of energy of activation (\(E_i\)) and preexponential multiplier (\(k_0i\)) the pole offered by S.M. Shestakov is used:

\[
\lg k_0i = 0.2 \cdot 10^{-4} E_i + 2. \tag{4}
\]

For definition of the temperature field the zone thermal calculation of the boiler P-49 furnace camera which has allowed to define the necessary number of local characteristics of its thermal work taking into account features of the movement of the environment was carried out. The furnace camera of boiler was divided into separate zones (two on depth and four on height fire chambers), with calculation of the each zone sizes, the areas of the heat-absorbing surfaces of the screens protecting each zone (or the intra furnace screens included in zone in case of existence), and the areas of surfaces of radiation of the next zones.

For assessment of the reaction No. 4 of system (2) in burning out of carbon particle influence extent Semenov (Se) criterion characterizing the relation of flow of the substance absorbed by homogeneous reaction of afterburning No. 4 to its diffusion flow is used:

\[
Se = \left(\frac{k_4 \Delta^2}{D}\right)^{1/2}, \tag{5}
\]

where \(k_4\) – constant of speed of reaction No. 4 of the equations system (1); \(\Delta = \delta/\text{Nu}_{10}\) – thickness of the given boundary film, m; \(D\) – coefficient of diffusion, sq.m/s.

For the accounting of mass exchange near carbon surface the method of "the given film" is used. The diffusion coefficient in multi-component mixture is defined from Uilk's ratio, and coefficients of mutual diffusion of substances under real conditions are determined by Vinkelman's dependence.

Expression for flow of the carbon which is burning out from the particles surface was a result of the solution of the equations system (1), (kmol/(m²·s)):

\[
G_c = \frac{\alpha_D}{RT} \left[ \frac{N_3}{1+N_3} p_{CO,\lambda} + \frac{N_3}{1+N_3} \left( p_{O,\lambda} + 0.5 p_{H_2,\lambda} \right) + \frac{N_5}{1+N_5} p_{N_2,\lambda} \right], \tag{6}
\]

and at the same time to calculate decrease of particle weight and size on expressions:

\[
\frac{dm}{d\tau} = \frac{dm_{\text{new}}}{d\tau} + \frac{dm_{\text{lost}}}{d\tau} + \frac{dm_{C}}{d\tau} = -G_c \cdot M_c \cdot \pi \cdot \delta^2, \ \text{kg} / \text{s}; \quad \frac{d\delta}{d\tau} = -\frac{2M_c}{\rho_c} \cdot G_c, \ \text{m} / \text{s}, \tag{7}
\]

where \(M_c = 12 \ \text{kg/kmol}\) – the molar mass of carbon; \(m = \pi/6 \cdot \delta^3 \cdot \rho\) – mass of spherical particle, kg; \(f_{\text{new}} = \pi \cdot \delta^2 \cdot \rho\) – the external surface area, m².

Calculations have shown that process of burning proceeds in intermediate area according to the scheme of the double burning interface (Se > 100), (case of "wet" gasification), the figure 2.

**Figure 2.** Distribution of partial pressures (a) and flows (b) of the components in the given film of coarse ash particle: 1 – O₂; 2 – CO₂; 3 – CO; 4 – H₂; 5 – H₂O; 6 – NO; 7 – N₂; the "0" indexes – particle surface; "\(\Delta\)" – flow
Distribution of concentration of NO on the fire chamber section (the field of concentration) in the known field of gas flow speeds, was defined by the numerical decision (the scheme "against flow" of the differential equation of mass exchange in the presence of the source member (NO generation zone):

\[
\frac{\partial}{\partial \tau} (\rho \cdot C_{NO}) + \nabla \cdot (\rho w C_{NO}) = \rho D_{NO} \nabla^2 C_{NO} + J_{NO},
\]  

(8)

where \(C_{NO}\) – mass concentration of nitrogen oxides; \(w\) – speed of gas flow; \(D_{NO}\) – average effective coefficient of NO diffusion in the mix of furnace gases; \(J_{NO}\) – intensity of generation of nitrogen oxides (NO source power).

The amount of the nitrogen oxides which have decayed on surface of the burning carbon particles is calculated from balance of reaction:

\[
2 \text{NO} + \text{C} = \text{N}_2 + \text{CO}_2.
\]  

(9)

By the developed technique the algorithm and the program of calculation are made, their debugging and testing on the experimental data on LTS burning are made. The program has block construction that gives the chance to switch-off some blocks or to connect new to research separate stages of process.

4. Numerical researches of furnace process, analysis of generation and transformation of nitrogen oxides

Settlement researches of burning of fuel, generation and transformation of gaseous pollutants were conducted with use of mathematical model of P-49 boiler No. 7 (building A) of Nazarovsky state district power plant with low-temperature swirl technology of burning (figure 3).

**Figure 3.** Model of boiler of P-49 (building A)
Modernization of boiler of P-49 of Nazarovsky state district power plant on low-temperature swirl technology of burning, provides possibility of use in boiler of the dried nazarovsky brown coal prepared on the central dust-plant which heattechnical characteristics are given in table 1.

The analysis of heattechnical characteristics of design fuel and settlement estimates have shown that generation of sulfur oxides in the course of burning of fuel will not exceed level 1450...1600 mg/nm³ for dried condition, and 1000...1150 mg/nm³ for crushed nazarovsky brown coal that meets requirements of the existing standards (2000 mg/nm³). Concentration of nitrogen oxides were by calculation of polyfractional fuel burning process in LTS fire chamber of P-49 boiler considering its granulometric characteristics.

### Table 1. Heattechnical characteristics of dried nazarovsky brown coal

| Name                              | Symbol | Dimension | Dried nazarovsky BC |
|-----------------------------------|--------|-----------|---------------------|
| Moisture                          | $W'_t$ | %         | 24.0                |
| Ashes                             | $A'$   | %         | 10.0                |
| Sulfur                            | $S'$   | %         | 0.49                |
| Carbon                            | $C'$   | %         | 46.22               |
| Hydrogen                          | $H'$   | %         | 3.2                 |
| Nitrogen                          | $N'$   | %         | 0.49                |
| Oxygen                            | $O'$   | %         | 15.6                |
| The lowest heat of combustion     | $Q'_i$ | MDzh/kg   | 17.35               |
| Volatiles exit on dry ashless state | $V^{\text{daf}}$ | %      | 47                  |

Calculations of process of burning of polyfractional fuel are carried out in relation to the groups of particles (10 groups) received by the way of processing of the fuel sieving characteristic. The example of sieving curve processing is shown in the figure 4 in relation to dried nazarovsky brown coal. The average settlement size of the finest particles has made 44 microns (1st group). The size of the most coarsened particle $\delta_{01}$ has made 880 microns at the average size in the 10th group of 837 microns, the indicator of polydispersion $n = 1.36$.

![Processing of dried nazarovsky brown coal sieving curve](image)

**Figure 4.** Processing of dried nazarovsky brown coal sieving curve
($W' = 24 \%$, $A' = 10 \%$, $R_{100} = 70 \%$, $R_{200} = 40 \%$)

For definition of air-gas flows speed vectors in volume of boiler furnace, the settlement scheme (figure 5) which coordinates of characteristic points were set according to the coordinates given the project in three-dimensional space of the Cartesian system [12, 13] is used. Speeds of flows input of
air of the lower blasting, tertiary blasting of the lower and average tier are accepted according to design data and can vary depending on loading.

Vectors of air-gas flows speed (figure 6) considering characteristics of blasting (figure 5), were found with use of the Ansys Fluent program complex in nodal points of elementary cells (figure 7) into which the furnace camera crashed. At the same time the characteristic size of each of the elementary cells does not exceed 200 mm.

![Figure 5. Settlement scheme of the boiler P-49 LTS-furnace](image)

![Figure 6. Projections of air-gas flows speed vectors in the boiler P-49 LTS furnace chamber on coordinate axes](image)

![Figure 7. Nodal points for definition of air-gas flows speed vectors](image)

Fields of the main reacting gas components concentration for burning process calculation, were accepted characteristic of LTS of furnaces [11].

Temperatures in characteristic zones of LTS of boiler P-49 furnace for calculation of chemical reactions speed constants are determined as a result of zone thermal calculation (the figure 8, a) taking into account influence of installation of intra furnace screens.

Increase in the area of the heatperceiving fire chamber surface at installation of intra furnace screens reduced a settlement maximum of temperatures since 1400...1450 °C (in option without screens, the figure 8, b) till 1250...1300 °C (in option with screens, the figure 8, c). Besides, installation of intra furnace screens in the lower swirl zone, involves additional decrease in the temperature of gases at the exit from a fire chamber (on 50...100 °C) which will positively affect the work of the screen surfaces of heating located around an output window. Elimination of a high-temperature kernel of a torch, the tightened ignition in a combination to step air intake, decrease in a maximum of temperatures in the lower swirl zone of a fire chamber to level 1200…1300 °C, which is below than the temperature of the beginning of a fluid condition of ashes of nazarovsky brown coal (t_c = 1340 °C), will ensure reliable slag-free functioning of a boiler.

The aerodynamic picture of flows (figure 9) gives the chance to define flow speed vector in any point of the furnace camera and to use its projections to coordinate axes for calculations of trajectories of the polyfractional fuel reacting particles movement (figure 10). Fine particles (δ_{particles}<50...100 microns) burn out almost instantly, in time, not exceeding two seconds.
Figure 8. Results of zone thermal calculation of fire chamber of boiler of P-49 (LTS)

Figure 9. Vectors of air-gas flows speed in the volume of P-49 boiler LTS-furnace

Figure 10. Settlement trajectories of the reacting particles of dried nazarovsky brown coal

Figure 11. Concentration of nitrogen oxides in furnace section
Particles with sizes more than 100…150 microns, get to the lower swirl zone where circulate or before full burning out, or to exit in direct flow. Time of burning of these particles depends on their sizes and makes 2 up to 18 seconds.

The amount of the generated nitrogen oxides were summed up in elementary volumes of the furnace camera in which also their decomposition on the surface of the burning carbon, then results of calculation were averaged on width of fire chamber was considered and given to the chosen control section. The resulting field of nitrogen oxides concentration is shown in the figure 11. In relation to burning of dried nazarovskiy brown coal the maximum concentration of nitrogen oxides (800 mg/nm\(^3\)) are at back wall of fire chamber nozzle tertiary blasting above that most likely is caused by their intensive generation from the fine particles of fuel directing in direct-flow part of torch at once after exit from torches. Concentration of NO\(_x\) in the lower swirl zone are much lower and maintain at the level of 400...500 mg/nm\(^3\). Such concentration, despite burning out of bigger amount of fuel in the LSZ, are reached by step air intake in the course of particles repeated circulation and decomposition of NO on their burning surface. On the exit of a furnace, the resulting concentration of nitrogen oxides decrease and are approximately at 400 mg/nm\(^3\).

Thus, the developed model and the executed calculations have shown that as a result of modernization of P-49 boiler No. 7 of Nazarovsky state district power plant on low-temperature swirl technology of burning, it is necessary to expect considerably (almost triple decrease) emissions of nitrogen oxides; emissions of sulfur oxides – not exceeding requirements of the standard.

5. Results of the implementation of LTS technology on Nazarovsky state district power plant

Balance tests of boiler are carried out according to recommendations [19] in the range of loadings of 1000…1600 t/h at the parameters of superheated steam close to nominal; fuel when carrying out balance tests – coal dust of Nazarovsky brown coal. During balance tests technical, economic (inflows, losses of heat, electric power costs of own needs) and ecological (emissions of nitrogen oxides, sulfur oxides, CO) boiler indicators in the working range of loadings are defined.

In figures 12 and 13 dependences of heat loss are given, in figures 14 and 15 – dependence of efficiency (gross) from loading of cases A and B of boiler of P-49 respectively.

![Figure 12. Dependence of heat loss (q\(_i\)) on loading (D) hull "A": 1 – q\(_2\); 2 – q\(_4\)](image)

![Figure 13. Dependence of heat loss (q\(_i\)) on loading (D) hull "B": 1 – q\(_2\); 2 – q\(_4\)](image)

In the working range of loadings \((D = 500...800 \text{ t/h}) ((0.63...1.0)D_{nom})\) the following parameters are provided per one hull. The efficiency (gross) of the hull A with growth of loading changes from 92.5 % (at \(D = 500 \text{ t/h}\)) to 93 % (at \(D = 800 \text{ t/h}\)). Losses of heat with the leaving gases (q\(_2\), %) practically do not change with growth of loading and are at the level of 6.0...6.5%. Losses of heat with mechanical underburning (q\(_4\), %) with growth of loading do not change and make 0.3...0.6 %.
The similar picture of the change in losses as a function of the load takes place for the P-49 boiler hull B; the change in heat loss with the leaving gases is somewhat different (q₂, %) which is primarily due to use of old screen boiler superheaters on the hull B when carrying out modernization of (ShPP4,5 and ShVP2) which, most likely, resulted in insufficient heat removal and increase in temperature of the leaving gases. At rated load of efficiency of the hull B of P-49 boiler makes 92.5%. Work of boiler in all range of loadings happens at total absence of slagging.

The ecological indicators (emissions of nitrogen oxides, sulfur oxides, CO) reached after modernization are given in table 2.

**Table 2.** Ecological indicators of P-49 boiler No. 7 of Nazarovsky state district power plant after modernization on the LTS technology of burning

| Name                                             | Value                          |
|-------------------------------------------------|--------------------------------|
| The specified content of nitrogen oxides in the exit gases (at α =1.4, n.c.) CₙΟₓ, mg/nm³ | 365…400, 300…370, 370          |
| The specified content of sulfur oxides in the exit gases (at α =1.4, n.c.) CₕΟₓ, mg/nm³ | 480, 500, 2000                 |
| The specified content of carbon monoxide in the exit gases (at α =1.4, n.c.) C₃Ο, mg/nm³   | 105…215, 50…160, 300           |

**6. Conclusions**

Taking into account generation and conversion of nitrogen oxides in the combustion of organic fuel during low-temperature swirl burning (decomposition of nitrogen oxides on the burning coke particles) a new approach to the calculation and research of the fuel combustion in LTS furnace devices is developed and approved.

The mathematical model of calculating the polydisperse fuels burning process, which takes into account generation and conversion of pollutants in flue gases, is developed and tested on experimental data.

Using the developed model, a reliable estimate of the generation level of nitrogen oxides in the furnace chamber of boiler P-49 of Nazarovsky state district power plant planned for modernization for LTS technology of burning, was made.

As a result of modernization, the P-49 boiler was operated in the range of 1000…1600 t/h in double-hull mode, maintaining calculated steam parameters, high efficiency 90…93 %, total absence of slagging and the lowered concentration of nitrogen oxides is ensured (370…400 mg/nm³) and are sulfur (480…500 mg/nm³) in the leaving flue gases.
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