Research of nitrogen oxides generation during low-temperature swirl fuel combustion

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Abstract. The work is devoted to the solution of the issue of environmental protection from harmful emissions of thermal power plants. Mechanisms of nitrogen oxides generation in a low-temperature swirl furnace process are considered. The analysis of the combustion process characteristics influence on the final level of nitrogen oxide concentration in the flue gases of the boilers is presented. Calculations and experimental studies have shown that the method of low-temperature swirl combustion provides a significant reduction in emissions of nitrogen oxides to the atmosphere.

1 Principles and organization of low-temperature swirl furnace process

The concept of LTS-method (LTS-technology) was proposed by Professor V.V. Pomerantsev at the Leningrad Polytechnic Institute (now St. Peterburg Polytechnic University of Peter the Great) at the turn of the 1970s [1], and has been further developed now [2–4]. As an alternative to the pulverized-coal torch (Fig. 1a) [5–10], the method of low-temperature swirl combustion (Fig. 1b) has significant advantages, including, in particular, lower emissions of gaseous nitrogen oxides into the atmosphere [11, 12] .

The LTS method is based on the principle of organizing multiple circulation of relatively large fuel particles with periodic return to zones with the initial concentration of oxygen. In the LTS furnace, fuel is predominantly burned in the lower swirl zone, where multiple forced circulation of fuel particles is organized, which makes it possible to equalize the temperature field in the combustion chamber and to lower the temperature level in the furnace (on average by 100–150 K). The LTS-combustion method opens up great opportunities for reducing the dimensions of boilers and reducing metal costs due to an increase in the intensity of combustion and heat-mass exchange processes [13, 14].

The organization of repeated circulation of particles in the furnace and the creation of a stable fuel ignition zone made it possible to switch to combustion of grinded coal [15], which eliminated the danger of dust preparation system explosion and increased the boiler plant reliability as a whole.

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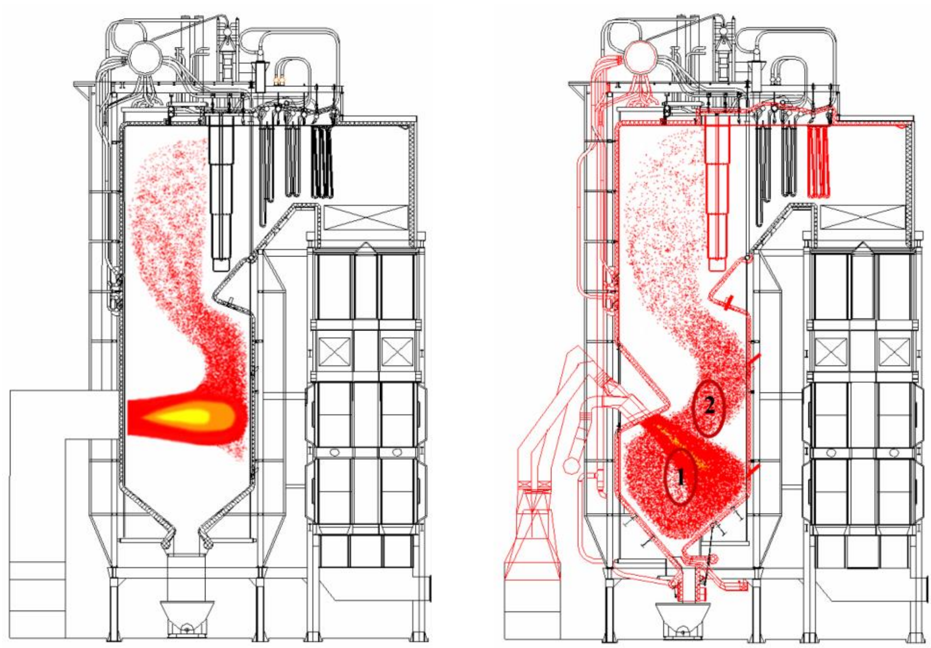


a) b)

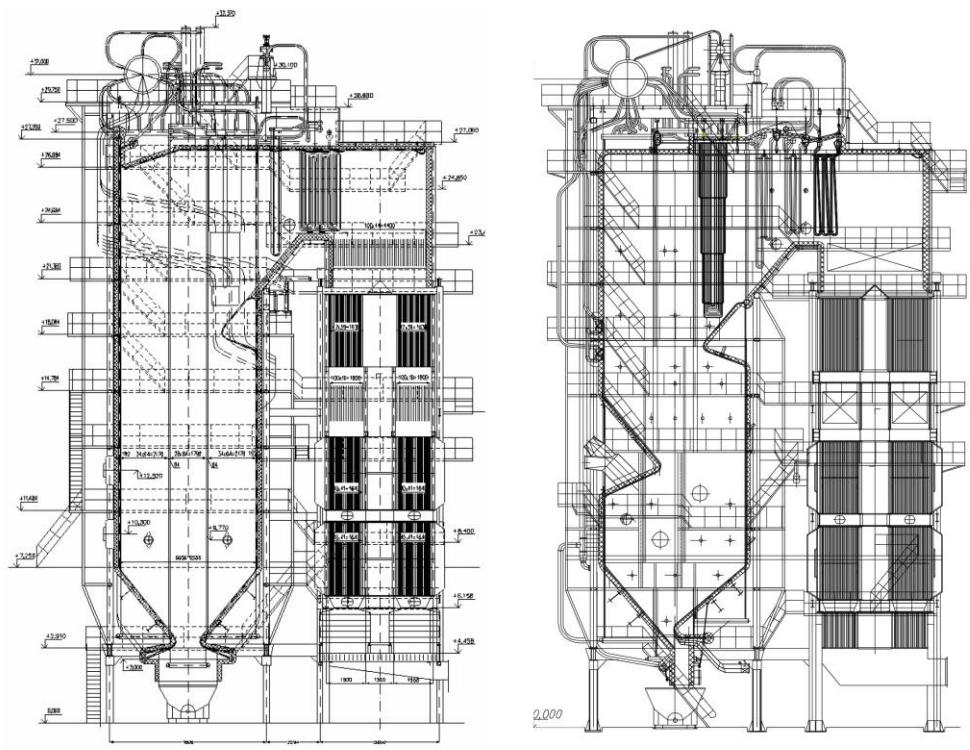
Fig. 1. Boiler with steam capacity of 210 t/h: a) – with traditional technology of pulverized coal combustion; b) – with low-temperature swirl technology: (1 – lower swirl zone, 2 – flow-through zone)

The use of the LTS method made it possible to organize efficient combustion of crushed fuel [15], thus completely eliminating the dust preparation system. Combustion of fuel in the LTS furnace occurs with high efficiency with the complete elimination of the liquid fuel use to illuminate the torch. At the same time, the temperature of the gases in the combustion chamber is reduced, and the slagging problems [16] of the heating surfaces are practically solved, the probability of high-temperature corrosion of the screens is reduced due to a decrease in the temperature level and a decrease in the oxygen concentration in the furnace, and the stepwise supply of the oxidizer to the flare leads to a decrease in the generation of toxic nitrogen oxides, formation of reducing zones, and decomposition of formed nitrogen oxides on the surface of burning coke particles [17].

2 Technical reequipment of the research object to the LTS combustion method and its results

The advantages of the low-temperature swirl method made it possible to realize it at many energy facilities, including the BKZ-210 boiler (station No. 9) of the Kirov TPP-4 (Fig. 2).

The boiler is vertical-water-tube, one-drum, with natural circulation, U-shaped configuration, with solid slag removal, with balanced traction, has the following design parameters: steam capacity D_{pp} = 210 t/h, superheated steam pressure p_{pp} = 13.8 MPa, superheated steam temperature T_{pp} = 813 K (540 °C). The nominal heat output of the boiler is Q = 143 MW (123 Gcal/h). One of the project fuels of the boiler is Kuznetsk coal of grades G and D, the characteristics of which are given in Table 1.



a) b)

Fig. 2. Boiler BKZ-210 st. No. 9 of Kirov TPP-4 before (a) and after (b) the technical upgrade to the low-temperature swirl combustion method

Table 1. Calculated characteristics of Kuznetsk coal of grades G, D

Name	**Designation**	**Dimension**	**Kuznetsk coal**
Moisture	W^r_t	%	11,2–22,3
Ash	A^r	%	13,2–22,3
Sulfur	S^r	%	0,2–0,4
Carbon	C^r	%	43,3–59,4
Hydrogen	H^r	%	3,1–4,3
Nitrogen	N^r	%	1,4–1,9
Oxygen	O^r	%	7,2–9,8
Net calorific value	Q^r_i	Kcal/kg	4119–5643
		KDj/kg	17245–23626
Ash (on a dry basis)	A^d	%	14,9–28,7

Commissioning tests on the boiler BKZ-210-140f st. No. 9 after its technical re-equipment for the LTS-combustion method was carried out according to the ORGRES method [18] according to the approved programs. The coefficient of efficiency of the boiler was determined by the inverse balance method with the introduction of corrections for the operating conditions for the selection of ash and was, depending on the boiler load, 89.35 % (at D_{pp} = 140 t/h) and 91.0 % (at D_{pp} = 250 t/h) with a maximum value of 91.99 % at a nominal boiler load of 210 tph (Fig. 3). The concentration of nitrogen oxides at the outlet from the boiler is within 350−500 mg / Nm^3 (Fig. 4), which on average meets the requirements of regulatory documents [19] (Table 2).

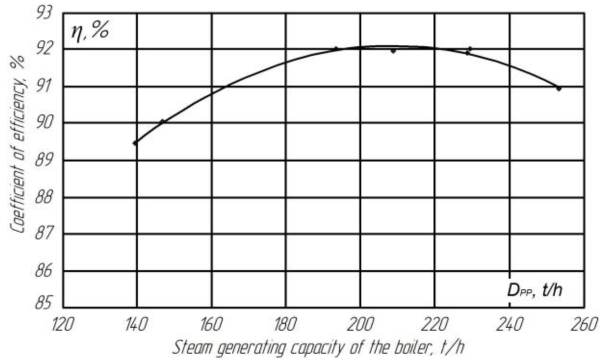


Fig. 3. Dependence of the gross boiler efficiency (η) on the load (D_{pp}) when operating on Kuznetsk coal

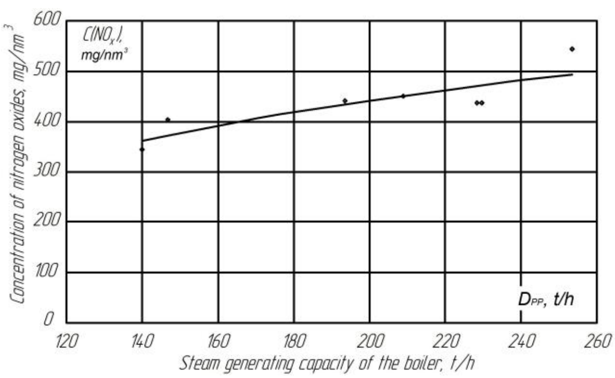


Fig. 4. The content of nitrogen oxides in the flue gases, depending on the load of the boiler when operating on Kuznetsk coal

Table 2. Ecological indicators of the boiler BKZ-210 st. No. 9 Kirov CHP-4 before and after technical re-equipment

Fuel	**Nitric oxide content $C(NO_x)$, mg/nm^3 at α=1,4**		
	Before technical re-equipment	**After technical re-equipment**	**Normative requirements [19]**
Kuznetsk coal G,D	Up to 1500	350–500	470

3 Generation of nitrogen oxides in a low-temperature swirl furnace

The degree of transition of fuel nitrogen (N_r) to nitrogen oxides (NO_x), in the experiments carried out on the BKZ-210-140f boiler before and after technical re-equipment on the LTS combustion method, was determined as the ratio of the measured nitrogen oxide concentration at the furnace outlet (NO_2''), to the maximum possible (under given conditions of the combustion process) concentration of nitrogen oxides, provided that all nitrogen of the fuel passes into nitrogen oxides $NO_{2\text{-"fuel"}}$:

$$\gamma_N = NO_2''/\,NO_{2\text{-"fuel"}}. \quad (1)$$

Concentration of NO_2 in terms of the volume of wet combustion products of fuel, (mg/nm^3):

$$NO_2'' = NO_{2\text{-meas}} \cdot (V^{dg}/V^{wg}), \tag{2}$$

where V^{dg}, V^{wg} – the volume of dry and wet combustion products per 1 kg of burned fuel, with the excess air factor corresponding to this experiment, nm3 / kg; $NO_{2\text{-meas}}$ – measured in the experiment concentration of NO_2, mg/nm^3.

The maximum possible (theoretical) concentration of nitrogen oxides (mg/nm^3):

$$NO_{2\text{-"fuel"}} = \frac{46}{14} \cdot 10^6 \cdot \frac{N^r}{100 \cdot V^g}, \tag{3}$$

where N^r – nitrogen content in fuel for the working mass, %; V^g – is the actual volume of combustion products, nm^3/kg.

Substituting NO_2'' and $NO_{2\text{-"fuel"}}$ in (1), we get:

$$\gamma_N = \frac{V^{wg} \cdot NO_{2\text{-meas}} \cdot 14}{46 \cdot 10^4 \cdot N^r}. \tag{4}$$

The degree of transition of nitrogen of fuel in NO_x, determined with reference to the BKZ-210 boiler prior to the technical re-equipment during coal combustion under the scheme of a direct-flow pulverized coal torch (γ_{N-DPCT}), was 0.23. The obtained value is in good agreement with the results of calculations for the dependence obtained by Blair D.W. for the mass fraction of the nitrogen output of fuel from the ignition temperature of fuel T, K, and the yield of volatiles on the combustible mass V^{daf},%:

$$\gamma_N(T, V^{daf}) = \frac{0,4861 V^{daf} + 3545 \exp(-85700/(RT))}{1 + 3545 \exp(-85700/(RT))}, \tag{5}$$

where: R=8.31 Dj/(mol·K) – universal gas constant.

After technical re-equipment for low-temperature swirl combustion, the value of the nitrogen transition of the fuel in NO_x (γ_{N-LTS}) is 0.05–0.08, which is, on average, 3–4 times lower than when burning coal dust in a direct-flow torch (Table 2).

Table 2. The degree of nitrogen transfer of fuels to nitrogen oxides during combustion of Kuznetskiy coal in boiler BKZ-210 st. № 9 of Kirov TPP-4

Value	Kuznetsk coal D, G	
	Before technical re-equipment	After technical re-equipment
The degree of transition of nitrogen of fuel in NO_x	γ_{N-DPCT}=0.23	γ_{N-LTS}=0.05–0.08

Calculations to determine the degree of nitrogen fuel transition in NO_x, carried out in [20] for LTS incineration and incineration in direct-flow pulverized coal torch (DPCT), show that the degree of transition of nitrogen-containing fuel compounds to NO depends on the method of fuel combustion, the temperature level in the combustion chamber, the excess air ratio and the nitrogen content of the fuel (Fig. 5). These data correspond to the results obtained on the boiler BKZ-210 of Kirov CHPP-4 with LTS-combustion technology [21, 22]. The value of $\gamma_N = f(N^r)$, described by curve 1 of Fig. 5, tends to 0,07–0,09 with increasing nitrogen content in fuel (N^r) to 1,9–2,0 %.

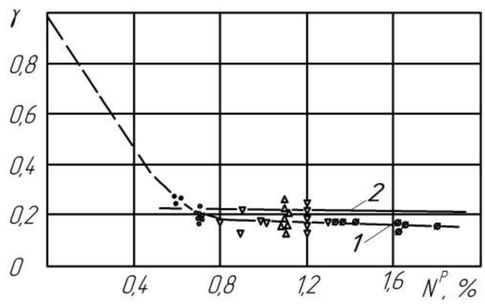


Fig. 5. Dependence of the degree of transition of nitrogen compounds of fuel in NO_x on the nitrogen content of the fuel: 1 – according to the tests on the boiler PK-24 st. No. 9 [20]:
• – Neryungri coal; o – Irsha-Borodinsky coal; ∇ – Azey coal; Δ – mixture of Azei and Cheremkhovo coals; ∅ – Kuznetsk coal; 2 – according to VTI for boilers burning dust from Ekibastuz and other hard coal

4 Model of low-temperature swirl process and combustion of fuel of polyfraction composition

Reduction of the degree of fuel nitrogen transfer to nitrogen oxides during the transfer of the boiler to the LTS combustion method and a significant increase in its environmental performance is explained by the peculiarities of the aerodynamic organization of the movement of gas-air flows in the LTS furnace and the use of fuel of coarse grinding. To study this process, with reference to a BKZ-210 boiler with an LTS furnace (Fig. 6), a mathematical model of fuel combustion was developed that takes into account the generation and conversion of nitrogen oxides.

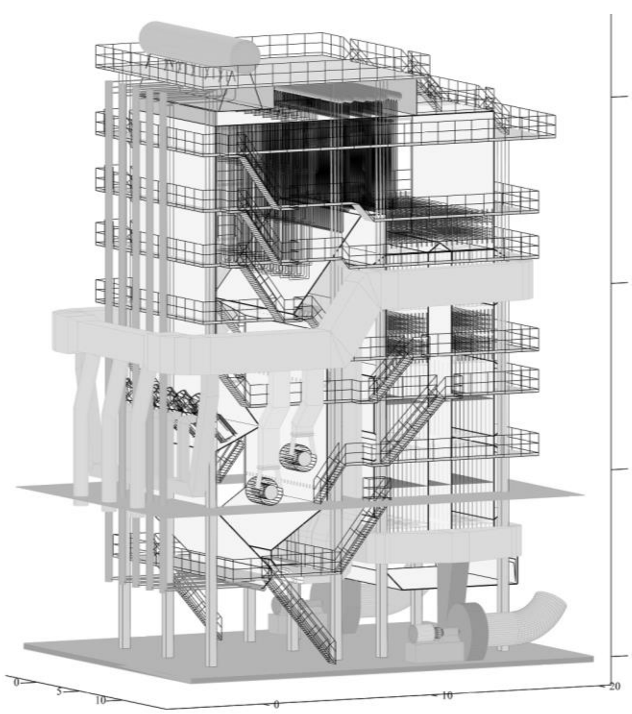


Fig. 6. Model of the boiler BKZ-210 of Kirov TPP-4 with low-temperature swirl combustion technology

Consideration of the combustion process from the diffusion-kinetic positions made it possible to compile a system of nonlinear differential equations of diffusion and kinetics of the type [23]:

$$dG_j = -(D/RT)\cdot(d^2 p_j/dx^2)dx; \quad G_j = (\alpha_D/RT)\cdot(p_j - p_{j0}); \quad dG_i/d\tau = C_i \cdot k_i, \qquad (6)$$

taking into account the oxidation and reduction reactions of particles coming on to the surface, and homogeneous reactions occurring within the boundary layer, and obtain an expression for determining the carbon flow from the surface of burning coke particles (kmol/(m^2·s)):

$$G_c = \frac{\alpha_D}{RT}\left[\frac{N_3}{1+N_3}p_{CO_2\Delta} + \frac{N_{3'}}{1+N_{3'}}\left(p_{O_2\Delta} + 0,5p_{H_20\Delta}\right) + \frac{N_5}{1+N_5}p_{NO\Delta}\right]. \qquad (7)$$

To solve the problem, the concepts of "reduced film" ($\Delta/\delta = 1/(Nu_D - 2)$); are applied; dimensionless coordinate ($\xi = x/\Delta$); criterion of Semenov ($Se = (k_{4'}\cdot\Delta/D)^{0,5}$); diffusion-chemical criterion ($N_i = k_i/\alpha_D$); the Arrhenius relation for reaction rate constants ($k_i = k_{0i}\cdot exp(-E_i/RT)$); "Poles" with coordinates k* = 100 m/s, T* = 2600 K; activation energy.

As a result of the calculations, the burnup curves of particles of Kuznetsk coal of various sizes (Fig. 7), trajectories of their movement to complete combustion (Fig. 8a) and the concentrations of nitrogen oxides in the sections along the height of the combustion chamber of the LTS furnace are determined (Fig. 8b).

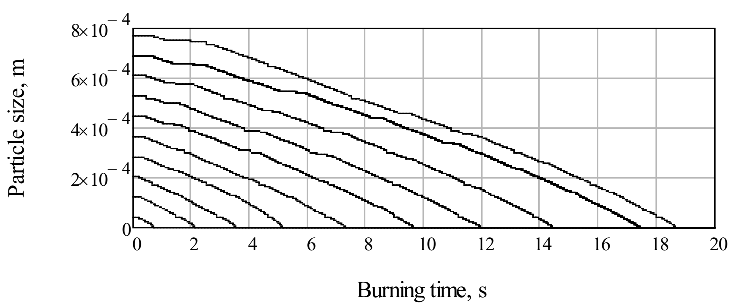


Fig. 7. Burnout of particles of Kuznetsk coal of various sizes in the LTS-furnace of the boiler BKZ-210 st. №9

Applied to the explored scattering characteristics of Kuznetskiy coal ($R_{100} = 30$ %, $R_{500} = 1$ %), the burning time of the smallest particle ($d_{min} = 40.6$ μm) is ~ 0.7 s, and the time of complete combustion of the particle of maximum size ($d_{max} = 780$ μm) is within 19 seconds.

The amount of nitrogen oxides reacted with the carbon surface of burning coke particles was from the balance of the reaction:

$$2\ NO + C = N_2 + CO_2, \qquad (8)$$

taking into account the carbon consumption of the coke reacted according to this reaction:

$$G_{C\_NO} = \frac{\alpha_D}{RT}\left(\frac{N_5}{1+N_5}p_{NO\Delta}\right). \qquad (9)$$

The calculated results (Fig. 8b) are in good agreement with the experimental data obtained on the BKZ-210 boiler with low-temperature swirl combustion technology

(Table 2). To the exit from the furnace, the concentration of nitrogen oxides in the flue gases is at the level of 350–500 mg/nm^3; the same NO concentrations are fixed during the operation of the boiler.

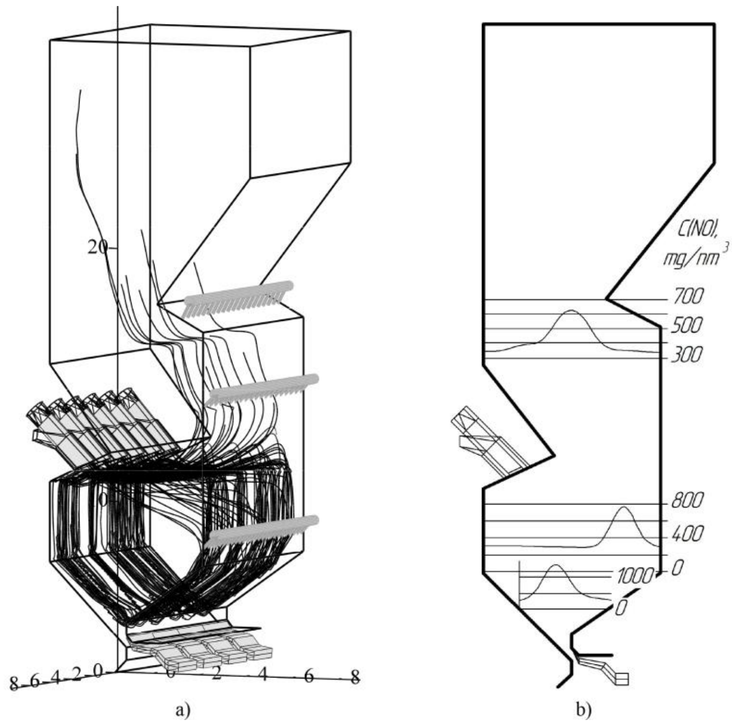


Fig. 8. Calculated trajectories of the motion of reacting particles of Kuznetsk coal (a) and the concentration of nitrogen oxides (b) in the LTS furnace of the boiler BKZ-210 st. No. 9

5 The results of the study, their analysis and discussion

The high ecological indexes of the LTS combustion method have been confirmed by calculation and experimental methods. With regard to the boiler BKZ-210 Kirovsk CHPP-4 with LTS-furnace, a three-fold reduction in emissions of nitrogen oxides was recorded in comparison with the technology of the direct-flow charcoal flare. Swirl aerodynamics LTS-furnaces and step-by-step supply of oxidizer to fuel affect the generation of nitrogen oxides by the following mechanisms:

1. The combustion process in the lower swirl zone, where the bulk of the fuel burns (Fig. 8a) occurs in the absence of an oxidizer. A decreased concentration of oxygen (Fig. 9a) entails a decrease in the generation of "fuel" nitrogen oxides formed at the initial part of the flare (at the stage of escape and combustion of the volatile substances of the fuel).
2. The formed nitric oxides under the conditions of the reducing medium (Fig. 9b, 9c) react intensively by the reaction (8) with the carbon of the coke, which also reduces the total concentration of NO.

The two-nozzle scheme of the bottom blast ensures the separation of fuel particles in the flow along the front slope of the furnace funnel. Small (for the considered fineness of grinding) particles ($\delta_{particles} < 250–280$ μm) pass along the front ramp without touching the furnace shields (Fig. 10a) quickly enough, but considering their large amount, they make a significant contribution to the decomposition of nitrogen oxides on its surface. In turn, the large particles (Fig. 10b) stay near the front edge of the furnace funnel for a considerable time (while being in a reducing medium (Fig. 9b, 9c)), which increases the amount of NO_x reacted with the coke carbon by reaction (8). In general, calculations show that burnout of particles of any size in the lower swirl zone of the LTS furnace contributes to a decrease in the concentration of nitrogen oxides in flue gases.

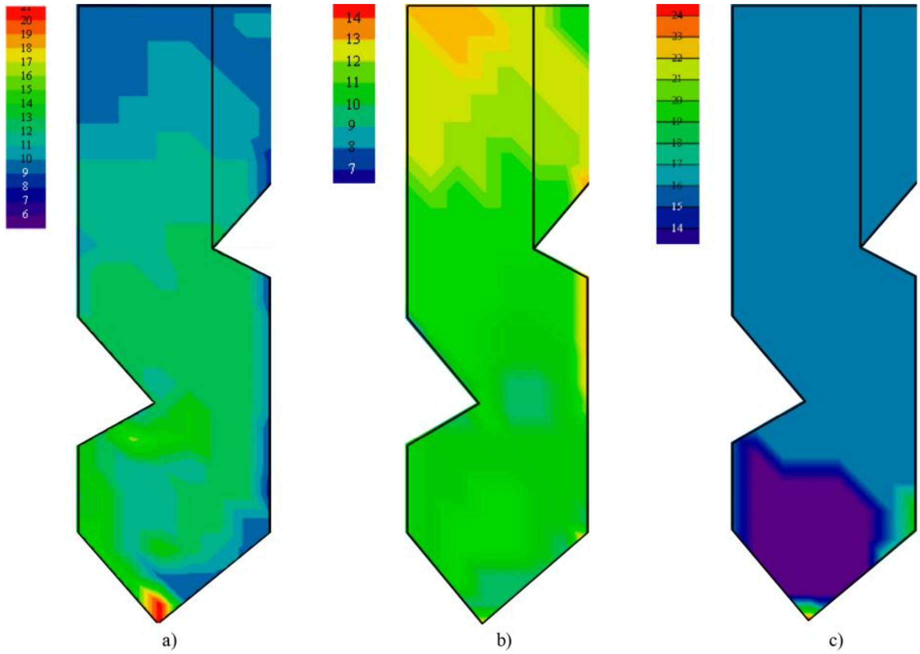


Fig. 9. Concentrations of the main reactive components in the LTS furnace of the boiler BKZ-210 st. No. 9 of Kirov CHPP-4: a) – O_2; b) – CO_2: c) – H_2O

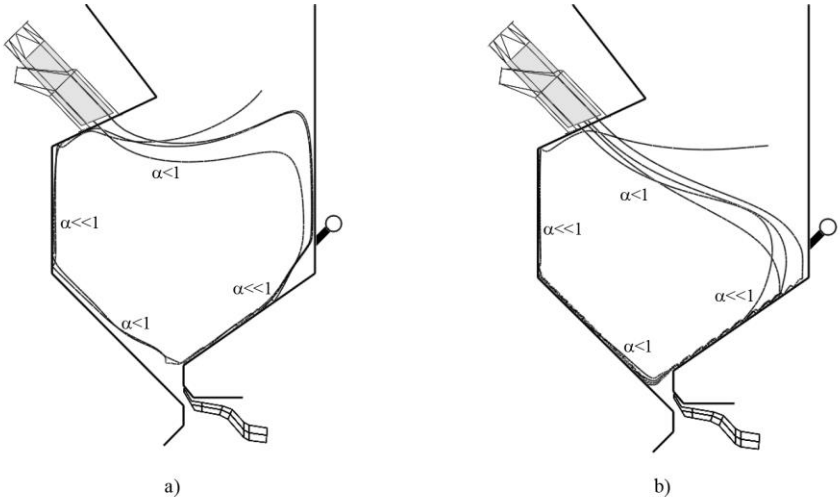


Fig. 10. The excess air coefficients in the combustion region of small ($\delta_{particles}$ < 250 ... 280 μm) – (a), and large ($\delta_{particles}$ > 300 μm) – (b) fuel particles

6 Final provisions and conclusions

As a result of the calculation study, the main parameters that influence the process of nitrogen oxide generation during low-temperature swirl combustion of fuel are revealed. The parameters studied include the particle size distribution of the fuel, the aerodynamics of the combustion chamber created by combustion air and lower blast air streams, the concentrations of the main reactive components, and the temperature level in the low-temperature swirl furnace

The organization of a stepped supply of oxidant to the fuel (burnt air, bottom and tertiary blasting) tightens the ignition process, reduces local maximum temperatures in the furnace, inhibits the generation of nitrogen oxides and significantly contributes to their reduction. At the same time, the presence of a stepped air supply has a positive effect on the aerodynamic structure of gas-fuel flows and the operation of the combustion chamber as a whole. The most intensive decomposition of the formed nitrogen oxides occurs in the lower swirl zone of the furnace, where the bulk of the fuel burns out.

In general, the proposed model makes it possible to reliably predict the generation of nitrogen oxides in the introduction of the low-temperature swirl combustion method, as well as enable analysis of the effect on the burning process of the main regime and constructive factors.

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