Numerical research of reburning-process of burning of coal-dust torch

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Abstract. This work is dedicated to numerical research of ecological indicators of technological method of decrease in emissions of nitrogen oxides at combustion of solid fuel in coal-dust torch to improve the energy efficiency of steam boilers. The technology of step burning with additional input in zone of the maximum concentration of pollutant of strongly crushed fuel for formation of molecular nitrogen on surface of the burning carbon particles is considered. Results of modeling and numerical researches of technology, their analysis and comparison with the experimental data of the reconstructed boiler are given. Results of work show that input of secondary fuel allows to reduce emissions of nitrogen oxides by boiler installation without prejudice to its economic indicators.

1. Introduction
The torch way of combustion of solid fuel in large power holds dominant position now. Combustion of powdered fuel in fire chambers in comparison with its burning in layered mechanical fire chambers causes high profitability of process of burning at the minimum excess of air and losses from chemical and mechanical underburning [1].

One of approaches to solution of the problem of increase in efficiency of combustion of coals is based on attempts of improvement of furnace process at preservation as basis of the existing technology of coal-dust burning in direct-flow torch. Shortcomings of this technology (pollution and slagging of surfaces of heating, high level of generation of NOx, operational problems) aim to solve due to increase in uniformity of heat release in volume to fire chamber, increases in dimensions of fire chamber, use of recirculation of gases, uses of systems with the dust flues of high concentration (DFHC) and other actions [2]. In too time, today, for power generation and heat solid fuel, is generally burned in powerful coal-dust boilers which work is followed by the increased emissions in the atmosphere of NOx [3] nitrogen oxides.

The greatest distribution in power was gained by technological methods of increase in ecological indicators of boilers which without demanding considerable capital expenditure, allow to provide, generally, acceptable concentration of pollutants in the leaving combustion gases [4–6]. The technology of input of additional (secondary) fuel above the main torches of boiler (reburning-process) [7–12], allows to achieve decrease in emissions of NOx, keeping at the same time economic indicators and efficiency of boiler installation at the required level. At the same time ~ 90 % (on heat) fuel consumption of design grinding move in the main torches, and ~10 % of the fuel having high milling – in the additional torches located above the main in zone of the maximum concentration of nitrogen oxides.
(figure 1). Further on the course of torch quantity of additional air for reburning of products not of full burning of [13–15] is entered.

![Figure 1. Scheme of the organization of three-stage burning ("reburning—process")](image)

Object of research is the research of possibility of increase in ecological indicators of coal-dust torch by input in zone of burning of the additional strongly crushed fuel for decrease in concentration of nitrogen oxides by their decompositon on the surface of the burning carbon.

Nitrogen oxides (NO\(_x\)) which are formed in the furnace camera consist generally of nitrogen monoxide (NO \(\approx 95\%\)), and only not considerable part is the share of nitrogen dioxide (NO\(_2\) \(\approx 5\%\)) [16]. On the mechanism of education they are usually divided on "thermal" (or "air"), which are formed of air nitrogen, and the "fuel" – formed of fuels nitrogen. The amount of the formed "thermal" nitrogen oxides, and also extent of transition of nitrogen of fuel to "fuel" NO\(_x\), are in strong dependence on temperature of furnace process and concentration of oxygen in zone of active burning [17].

2. Calculation procedure and mathematical model

Changes of torch temperature on height of the furnace camera are described by the formula offered by A. M. Gurvich and A. G. Bloch:

\[
\theta = \left( e^{-\alpha Z} - A \cdot e^{-\beta Z} \right)^{1/4},
\]

applicable for step burning transformed to the following formula:

\[
\theta = \left( e^{-\alpha Z} - A \cdot e^{-\beta Z} \right)^{1/4} \cdot b_1 + \left( e^{-\alpha (Z-Z_{max})} - A \cdot e^{-\beta (Z-Z_{max})} \right)^{1/4} \cdot b_{II},
\]

where: \(Z\) – relative distance from the place of input of fuel; \(Z_{max}\) – the position of maximum temperature in the furnace camera; \(\alpha\) and \(\beta\) – pilot coefficients, are accepted according to recommendations [18]; \(A=1-\theta_0^4\); \(\theta_0\) – dimensionless temperature on entrance to fire chamber.

Processing of the sieving characteristic as the main, and additional fuel, is carried out with dependence use Rozin-Rammier-Bennet of particle distribution of dust by the sizes:

\[
R_{ii} = \exp(-b \cdot \delta_{ii}^n),
\]
where: $R_{0i}$ – the relative mass content of particles with the size equal or more than $\delta_{0i}$; $b$ and $n$ – the pilot coefficients characterizing respectively subtlety of grinding and polydispersion of dust. For coal dust depending on grade of coal and type of mills of $n \ b$ coefficient – ranging from $4 \cdot 10^{-3}$ (rough dust) to changes ranging from 0.8 to 1.6, and $4 \cdot 10^{-2}$ (fine dust).

The size of the most coarsened particle $\delta_{0i}$ is defined from ratio:

$$\delta_{0i} = \left( m/b \right)^{1/n},$$

(4)

where $m$ – the parameter accepted equal 6.9. At the same time the size of the most coarsened particle is equal to diameter of openings of such sieve on which the rest makes 0.1% of mass of coal dust.

Burning of coal dust fuel carbon is considered with use of the main reaction:

$$C + O_2 = CO_2,$$

(5)

and reaction of the formed nitrogen oxides is described with the following reaction:

$$C + 2NO = N_2 + CO_2.$$

(6)

Constants of speed of reactions (5), (6) are presented in the form of dependence of Arrhenius:

$$k_{C+O_2} = k_0^{C+O_2} \exp \left[ -E_{C+O_2} / (RT) \right],$$

(7)

$$k_{C+NO} = k_0^{C+NO} \exp \left[ -E_{C+NO} / (RT) \right],$$

(8)

where $k_0^{C+O_2}$ and $k_0^{C+NO}$ – preexponential multipliers. $E_{C+O_2}$ and $E_{C+NO}$ – energy of activation of the corresponding reactions.

The preexponential multiplier for reaction of $C+O_2$ could be found by S. M. Shestakov’s pole:

$$\lg(k_0^{C+O_2}) = 0.2 \cdot 10^{-2} E_{C+O_2} + 2,$$

(9)

and energy of activation depends on type of the burned fuel.

The preexponential multiplier in expression (6) reactions of $C+2NO$ is accepted by equal $k_0^{C+NO} = 1.18 \cdot 10^4$, energy of activation $E_{C+NO} = 145000$ J/mol (according to Tang Biguang, Kazutomo Ohtake).

The size of mechanical underburning is defined at average effective temperature of torch which, in turn, depends on the $Z_{max}$ parameter defining the provision of maximum of temperatures in the furnace camera and temperature of gases at the exit from $9^\circ$ fire chamber.

Definition of possible time of stay of fuel in fire chamber is carried out on condition of dust particles motion with the speed of gas flow without lag that is admissible for conditions of direct-flow coal-dust torch. The relative size of the most coarsened particle by which the size of mechanical underburning is defined, is after definition of area of burning of fuel (kinetic, intermediate or diffusion). Results of the carried-out calculations have shown that burning out of polyfractional coal-dust torch happens, generally, in intermediate area [19].

Change of surface area of the reacting fuel on height of fire chamber is calculated with the next dependence:

$$F = \frac{6mn}{\rho_k \cdot \delta_{0i}} \int_{x}^{1} \exp(-my^n) \cdot \frac{(x+y-1)^2}{y^3} \ dy,$$

(10)

where: $\rho_k$ – density of coke, kg/m³; $x = \delta_i / \delta_{0i}$ – the relative size of the most coarsened particle; $y = \delta_{0i} / \delta_{0i}$ – the relation of the initial size of particle $i$-th fractions to the initial size of the most coarse particle.

The amount of the formed nitrogen oxides is defined as the sum "fuel" and "thermal":

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$$\text{formed nitrogen oxides is defined as the sum "fuel" and "thermal":}$$
\[
\hat{N}_{\text{NO}} = C_{\text{NO}}^{\text{fuel}} + C_{\text{NO}}^{\text{term}},
\]

(11)

Amount of the thermal nitrogen oxides which are formed on reactions:

\[
\begin{align*}
O + N_2 & \xrightarrow{\Delta} NO + N, \\
N + O_2 & \xrightarrow{\Delta} NO + O,
\end{align*}
\]

(12)

(13)
is determined by the dependence offered by Ya. B. Zeldovich, I. Ya. Sadovnikov and D. A. Frank-Kamenetsky:

\[
d\frac{\text{d}NO}{\text{d}\tau} = \frac{5 \cdot 10^{11}}{O_2^{1/2}} \cdot \exp[-86000/(RT)] \cdot \left\{ \frac{O_2 \cdot N_2}{3} \cdot \frac{64}{\exp[-43000/(RT)]} - NO^2 \right\},
\]

(14)

where \(\tau\) – time, with; \(N_2, O_2, NO\) – concentration of components, kmol/l.

"Thermal" nitrogen oxides are formed in sufficient numbers at temperature \(T > 1800\) K, at smaller temperatures they can be neglected.

Final concentration of fuel nitrogen oxides is determined by the technique constructed on results of laboratory researches of employees of VTI of Dzerzhinsky in which connection between design features of torches and furnace devices, on the one hand, and parameters of torch process of burning, was established with another.

The number of emissions of nitrogen oxides of the boiler \(M_{\text{NO}}\) g/s is calculated on specific emissions of \(K_{\text{NO}}\), g/MJ:

\[
M_{\text{NO}}^{\text{fuel}} = B_{\text{p}} \cdot Q_{\text{i}}^{\text{fuel}} \cdot K_{\text{NO}}^{\text{fuel}},
\]

(15)

\[
K_{\text{NO}}^{\text{fuel}} = k \left\{ \left(10 \cdot N^4 \right) / Q_{\text{i}}^{\text{fuel}} \right\} \xi_{\text{cm}} \xi_{\text{m}} \xi_{\text{r}},
\]

(16)

where \(\xi_{\text{cm}}, \xi_{\text{m}}, \xi_{\text{r}}, \xi_{\text{n}}\) – are the pilot coefficients considering coefficient of excess of air in torch, share of primary air in torch, share of recirculation of combustion gases in primary air, value of the maximum temperature on the site of formation of NOx, mixture formation at the root of swirl torches, the parameter of swirl torches twist.

Thus, concentration of fuel nitrogen oxides, g/m\(^3\), will be equal:

\[
C_{\text{NO}} = (Q_{\text{i}}^{\text{fuel}} \cdot K_{\text{NO}}^{\text{toppl}}) / V_{\text{S.G.}},
\]

(17)

When calculating dynamics of change of concentration of fuel nitrogen oxides it is considered that their education happens during exit and combustion of flying. Definition of time of exit and combustion of flying is carried out on dependences:

\[
\begin{align*}
\tau_{v.1} &= k_{v.1} \cdot 10^{13} T_{g}^{n_{v.1}} \delta_{m_{v.1}} (1 + w_{\text{cm}}^{n_{v.1}}), \\
\tau_{g.1} &= k_{g.1} \cdot 10^{10} T_{g}^{n_{g.1}} \delta_{m_{g.1}} (1 + w_{\text{cm}}^{n_{g.1}}),
\end{align*}
\]

(18)

(19)

where \(k_{v.1}, n_{v.1}, m_{v.1}, \delta_{v.1}, k_{g.1}, n_{g.1}, m_{g.1}, \delta_{g.1}\) – pilot coefficients.

Amounts of the decayed nitrogen oxides is defined on surfaces of coke particles according to stoichiometry of a reaction (6). Coke carbon burning out speed on this reaction could be described by the following formula:

\[
G_{C_{\text{NO}}} = \frac{\alpha_{D}^{C_{\text{NO}}}}{RT} \cdot \left\{ \frac{N_{C_{\text{NO}}} \cdot P_{\text{NOx}}}{1 + N_{C_{\text{NO}}} \cdot P_{\text{NOx}}} \right\}, \text{kmol}/(\text{m}^2 \cdot \text{s}),
\]

(20)
where $\alpha_D^{CNO} = (\text{Nu}_D D) / \delta$; – coefficient of diffusion mass exchange, $\text{Nu}_D$ – diffusion criterion of Nusselt; $D$ – diffusion coefficient; $R = 8.314 \text{ J/(mol·K)}$ – universal gas constant; $N_{CNO} = k_{CNO}/\alpha_D^{CNO}$ – diffusion and kinetic criterion of reaction; $P_{NO_A}$ – the partial pressure NO.

Amount of the reacted nitrogen oxides, kg:

$$\text{NO}_{react} = 2.5 \cdot G_{CNO} \cdot 12 \cdot F \cdot \Delta \tau,$$

where $\Delta \tau$ – time interval.

In the place of input of tertiary blasting there is reburning of the products of incomplete combustion arriving from recovery zone on reaction:

$$2\text{CO} + \text{O}_2 = 2\text{CO}_2 + 571 \text{ kJ/kmol}.$$  

Preexponential multiplier of this reaction of $k_{04} = 7 \cdot 10^6 \text{ s}^{-1}$, energy of activation of $E_4 = 96800 \text{ kJ/kmol}.$

By the stated technique the mathematical model and the computer program allowing to carry out calculations of burning out of coal-dust fuel in torch, assessment of emissions of nitrogen oxides and extent of influence on their concentration of constructive characteristics and regime parameters of work are developed.

3. Results of modeling and numerical research, their discussion and analysis

By the developed technique calculations of process of burning in boiler are carried out TPE-214 of the Novosibirsk CHPP-5 (figure 2) reconstructed on technology of three-stage burning. Rated fuel of boiler is mix of the Kuznetsk coals of brands G and D with the following characteristics: $Q_r = 20.52 \text{ MJ/kg}$, $A'_r = 17.6 \%$, $W' = 12 \%$, $N'_r = 1.8 \%$, $V_{daf} = 42 \%$.

Step burning ("reburning–process") on boiler of TPE-214 is realized as follows [20, 21]. Ready coal dust (figure 3) with grinding subtlety ($R_{90, osn} = 25 \%$) that is much higher, than at additional fuel ($R_{90, dop} = 7 \%$), is transported by the drying agent to the main torches of the lower tier.

Preparation of dust of additional fuel for ensuring work of torches of step of recovery, is carried out in separate dust system. Transport of dust is carried out by drying inert gases on four tangentially located torches of recovery step placed 8 meters above the main torches. Recovery torches supply 14 % of total quantity fuel.

On boiler of TPE-214 NTEC-5 employees of SibKOTES have carried out measurements of indicators of work after reconstruction on step burning technology. In relation to the settlement scheme of boiler TPE-214 (the figure 4, a), the profile of temperatures on fire chamber height calculated on dependence (2) on the nature of change matches the profile received during experiences, however actual temperatures of torch were slightly lower (settlement figure 4).

Change of concentration of nitrogen oxides on height of the furnace camera is shown in the figure 4. Differences in the nature of formation of nitrogen oxides on the initial site appear owing to the accepted formation mechanism of NO (formation of NO during time of exit and combustion of flying).

According to results of experiences, total exit of nitrogen oxides made at one-stage burning 800...900 mg/m3. At implementation of three-stage burning authors [21] managed to achieve decrease in concentration of nitrogen oxides on 350...420 mg/m3 that satisfies acting normative act [22].

The calculated value of concentration of nitrogen oxides – 431 mg/m3 has turned out above pilot value – 375 mg/m3. This results from the fact that time of stay of particles in fire chamber is determined by settlement technique in the assumption that particles move with speed of gases in the ascending flow. At the same time increase in time of stay of particles in fire chamber at the expense of its tangential design is not considered. Also the error brings higher values of furnace temperatures received in the settlement way in calculations.

For assessment of economic indicators of transfer of boiler into step burning, numerical researches of influence on economic indicators of boiler are conducted (size q4) of height of installation of additional torches and share of secondary fuel (figure 5).
Figure 2. Boiler of TPE-214 (longitudinal section)

Figure 3. Sieving characteristic of the basic ($R_{90_{osn}} = 25\%$) and additional fuel ($R_{90_{dop}} = 7\%$); (—— main fuel; ———— additional fuel)
Figure 4. a) – Settlement scheme of boiler TPE-214; b) – Torch temperature; c) – Concentration of nitrogen oxides on fire chamber height (— results of calculation; — experimental data)

Figure 5. a) – Influence of height of additional fuel torches installation on the value of mechanical underburning (q4); b) – Influence of secondary fuel share on the value of mechanical underburning (q4); (— — — — — R_{90\_dop} = 37 %, R_{200\_dop} = 4 %; — — — — — R_{90\_dop} = 24 %, R_{200\_dop} = 3 %; — — — — — R_{90\_dop} = 14 %, R_{200\_dop} = 1 %)

At increase in height of installation of additional fuel torches, the value of mechanical underburning (q4) slightly grows (the figure 5, a) that is connected with smaller time of stay of particles of recovery fuel in fire chamber. At the same time, as show calculations, the tier of additional torches is established below, the smaller concentration of nitrogen oxides turns out at the exit from fire chamber. So, at
installation of torches of secondary fuel is 3 meters higher than the main tier of torches, final concentration of nitrogen oxides makes $C_{NO} = 288 \text{ mg/m}^3$, and at installation is 15 meters higher – $C_{NO} = 383 \text{ mg/m}^3$.

Change of concentration of nitrogen oxides on fire chamber height depending on share of the secondary fuel given to upper tier happens as follows. The smallest concentration of nitrogen oxides ($C_{NO} = 187 \text{ mg/m}^3$) is reached at input of 25 % of fuel through tier of recovery torches that is also followed by growth of mechanical underburning of secondary fuel. At input of 10 % concentration of nitrogen oxides at the exit makes $C_{NO}$ of fire chamber $= 297 \text{ mg/m}^3$.

Analyzing the received dependences, it is possible to draw conclusion that increase in share of secondary fuel reduces temperature in the main zone of burning, reduces final concentration of nitrogen oxides at the exit from fire chamber, however leads to some growth of mechanical underburning of secondary fuel.

4. Final clauses and conclusions

As a result of the conducted settlement research on the offered technique the key parameters exerting impact on efficiency of method of three-stage burning at its implementation on the coal-dust boiler equipped with direct-flow torches are revealed. The studied parameters are: fineness of secondary fuel grinding, height of recovery torches installation and share of the secondary fuel given through them.

The strongest influence on efficiency of decomposition of NO gives change of concentration (share) of secondary fuel in recovery zone. With the increase in share of secondary fuel up to 25 % of the basic efficiency of decomposition of nitrogen oxides can reach up to 70 % that is followed, in turn, by increase in costs of grinding, and growth of mechanical underburning. Combustion of the main fuel in smaller concentration allows to reduce temperature in the zone of active burning, which is vital at high temperatures in fire chamber and intensive formation of "thermal" nitrogen oxides.

Increase fineness of grinding and decrease in height of recovery fuel torches installation are approximately equally affect final concentration of nitrogen oxides at the exit from fire chamber. However, change of torches installation height is connected with configuration of the equipment in the boiler department, which results in need of the accounting of possibility of fuel air mixture and air ducts connecting to torches.

In general the offered model allows to predict authentically generation of nitrogen oxides at implementation of method of step burning and decomposition of nitrogen oxides on secondary fuel, and also gives the chance of the analysis of influence on process of burning of the major regime and efficiency factors.

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