PAPER • OPEN ACCESS

Moderate intensity chemical incomplete combustion of fuel

To cite this article: P Roslyakov *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1061** 012037

Moderate intensity chemical incomplete combustion of fuel

P Roslyakov[1], K Pleshanov[1], K Shchelchkov[2], V Rudomazin[3]

[1]Institute for Electrical Engineering and Electrification, Moscow Power Engineering Institute (MPEI), 14, Krasnokazarmennaya street, Moscow 111250, Russia
[2]Research and Development Department, Environmental Industrial Policy Centre (EIPC), 38, Stremyanny pereulok, Moscow 115054, Russia
[3]Engineering Department, Environmental Industrial Policy Centre (EIPC), 38, Stremyanny pereulok, Moscow 115054, Russia

E-mail: shchelchkovkirill@gmail.com

Abstract. The paper presents research results for NO_X reduction for moderate incomplete combustion, its impact on the environment and boiler reliability, optimal combustion conditions criteria, and its implementation in operating steam and hot-water boilers. The authors pay additional attention to the cost efficiency criterion while analysing the best method for reducing NO_X. After conducting a numerical calculation for combustion processes under certain defined conditions, the authors suggest a new method for emission reduction by suppression of thermal NO_X formation using the extended Zeldovich mechanism. Research shows up to 40% NO_X reduction potential for existing boilers depending on fuel type and operating conditions with CO concentration in stack gases lower than standard levels due to chemical incomplete combustion.

1. Introduction

Environmental issues draw major attention of researchers and practitioners in the modern world. Thermal power plants are pollution sources, which are studied in many aspects; in particular, they emit nitrogen oxides which contribute significantly to air pollution. Since the life cycles of most Russian boilers have nearly expired, it is not reasonable to implement costly emission reduction techniques; therefore, it is necessary to develop and implement low-emission fuel firing methods within existing boilers, these measures have low capital and operating costs and are quick to implement.

The intra-furnace methods of NO_X emission reduction are widely used in Russia. Unfortunately, their implementation for existing, outdated boilers cannot ensure an optimal combination of suppressing NO_X and complete fuel burnout. Implementation of these measures at the outdated boilers [1-3] has generally resulted in the efficiency reduction (due to the increase in incomplete combustion of fuel and stack gas temperature), operating reliability decrease (due to the growth of stack gas temperature and intensity of slagging), and less efficient control of NO_X emissions. That is why it is necessary to develop specific fuel firing methods for existing boilers that enable the significant reduction of NO_X emissions without affecting the performance of such boilers.

A new low-cost incomplete combustion method has been worked out by researches at Moscow Power Engineering Institute (MPEI) to solve this issue [4]. The method does not require significant reconstruction and can be implemented by thermal power plant personnel. It allows reducing NO_X emissions and boosting the performance of the steam generating unit as well as boiler performance.

Moderate intensity incomplete combustion logically continues low excess air firing [5-7]. Decreased air flow (to the furnace) facilitates suppressing the formation of thermal NO_X and fuel NO_X due to lower oxygen content.

2. Analysis of furnace process factors for fuel incomplete combustion

During boiler testing, concentrations of CO, benzo(a)pyrene (BaP), NO_X, and O_2 in combustion products were measured for the operation section (behind swiveling combustion chamber) and for the pilot section (behind the air heater) of the gas path for different modes of operation. For correct matching measured concentrations were recalculated for dry gases under standard conditions: temperature of 0℃, a pressure of 101.3 kPa, and air excess (in gases) ratio $\alpha = 1.4$.

Since CO concentrations in flue gases were measured for all boilers examined, we used this parameter in stack gases as one of the burning efficiency indexes. Experiments were conducted at 8 steam and hot-water “subcritical boiler” brands, in which superheated steam pressure did not exceed 13.8 MPa.

The experimental dependence of $NO_X = f(CO)$ at different fuel burning regimes showed significant NO_X reduction at moderate incomplete combustion with CO concentration level in stack gases up to 100 mg/m^3. Products of incomplete combustion in flue gas decrease NO_X reduction rate with further CO concentration increase in the flue gas.

CO is not the only product of incomplete fuel combustion; among byproducts, polycyclic aromatic hydrocarbons are formed as the result of burning solid and liquid fuels. Benzo(a)pyrene level was studied since it is the most toxic aromatic hydrocarbon and a highly carcinogenic substance.

Results of experiments show a lack of a direct relationship between changes in CO and BaP concentrations depending on excess air factor. Benzo(a)pyrene yield jumps during the initial growth of CO concentrations in stack gases from 0 to 20-30 mg/m^3.

After rapid initial growth, the BaP concentration growth rate in combustion products slows down and stops when CO concentration in stack gases reaches 300-400 mg/m^3 when the BaP level stays virtually the same depending on the kind of fuel you burn and boiler design.

Experimental results show that moderate incomplete combustion of fuel (with CO concentrations in boiler stack gases within the limits specified by the State Standard GOST R 50831-95 [8]) does not involve a significant increase in BaP concentrations; BaP concentration level stays below 100 ng/m^3. Experiments also show that main NO_X reduction occurs at the insignificant increase in BaP concentrations.

To assess the environmental impact of the combustion mode, it is necessary to take into account the masses and toxicity factors of all air pollutants present in boiler stack gases. For this purpose, we can use the total toxicity index Π_Σ [9, 10] of combustion products:

$$\Pi_\Sigma = \sum_{i=1}^{n} \Pi_i \tag{1}$$

where Π_i is a partial toxicity index, which refers to the specific amount of a pollutant and its relative toxicity and is the amount of pollutant m_i measured in grams and emitted from burning 1 gram of fuel divided by relative heat of fuel combustion and relative toxicity of the pollutant.

The partial NO_X toxicity index is initially -responsible for over 99.9% of the total toxicity index of combustion products at natural gas combustion.

With excess air reduction, the total contribution of partial toxicity indices for incomplete combustion products (CO and BaP) might increase up to 2-3% and at the same time Π_Σ decreases by half [2, 9-11].

Thus, experimental investigation results show that moderate incomplete combustion of fuel significantly decreases the adverse environmental impact of a boiler rather than increases it. And at the same time due to significant NO_X emission reduction total toxicity index decreases by 1.3-2 depending on the type of fuel used for the moderate incomplete combustion. They also show a steady reduction of NO_X concentration for different boilers and types of fuel in combustion products at incomplete combustion. Since reduction efficiency differs, it is necessary to determine optimal conditions for fuel incomplete combustion.

During the analysis of the furnace process, factors for incomplete combustion of fuel the authors considered: (1) NO_X formation mechanism; (2) the highest possible NO_X reduction level; (3) optimal conditions for the highest possible reduction of NO_X.

3. Numerical Experiment for Modelling Combustion

A numerical experiment was conducted for modeling natural gas combustion in the steam boiler E-420-13.8-140 [11]. Results of thermal calculations and experimental measurements of temperature along the flame length T_f [1,12] were taken as the initial data. Calculations were made assuming that (1) fuel, air, and combustion products were perfectly mixed; (2) there was no air inflow along the gas-air path in the boiler; (3) the temperature varied linearly along the length of the flame and (the boiler) gas path T(τ); (4) they were functions of time; (5) NO and CO concentrations were normalized to standard conditions.

The volume of the air/fuel mixture entering the combustion chamber is linearly dependent on excess air in the flame. Total gas volume V_g drops with the decrease in excess air:

$$V_g = V_g^0 + 1.0161 \times (\alpha - 1) V_a^0 \tag{2}$$

where V_g^0 − the theoretical volume of combustion products of 1 kg (1 m^3) of fuel, V_a^0 − the theoretical air required to completely burn 1 kg (1 m^3) of fuel. The time needed to reach maximum temperature increases and the combustion process lasts longer.

Experimental data [1, 12] show that in the case of conventional combustion of gas and fuel oil with excess air τ_α = 1.05 the average time needed to reach maximum temperature is 500 msec. Thus, the numerical experiments were conducted assuming that the time (msec) needed for furnace gases to reach T_{max} is a linear function of excess air in the first stage:

$$\tau_\alpha = \tau |_{\alpha=1.05} \times \frac{1.05}{\alpha} \tag{3}$$

This relationship was used to calculate the time, during which combustion products remained in the furnace and gas pipe of a boiler.

NO_X concentrations do not reach equilibrium values during combustion in boiler furnaces [13-15]. In fact, the yield of NO_X depends on (1) residence time in the maximum temperature zone, (2) maximum temperature level, and (3) excess air in this zone.

Previous calculations [1] showed that, with high accuracy, the gas temperature profile can be considered a piecewise linear function of residence time T = f (τ) in the gas path of a boiler.

Experimental investigation of moderate incomplete combustion of natural gas showed a 1-2 K change in the exhaust gas temperature T_{yx} compared to conventional combustion. It is less than the error of measurement. Therefore, the T_{yx} value was considered constant and independent of α during full-scale tests and numerical experiments.

To estimate each reaction contribution to NO_X formation or de-oxidation we used the ratio of the reaction (with lower index i) rate integral to the sum of the rate integrals of all n reactions of NO formation or de-oxidation:

$$\Delta = \frac{\int_0^{\tau_p} Wid\,\tau}{\sum_{j=1}^{n} \int_0^{\tau_p} Wid\,\tau} \tag{4}$$

The numerical experiments showed that the fuel combustion occurred at a sufficiently low temperature of 1300 K. In the case of the ideal mixture, the methane burns up pretty fast; its concentration drops to zero within 30-40 msec, and carbon dioxide concentration increases to its maximum value. This is where the first CO concentration peak that is several times bigger than the equilibrium concentrations is reached in combustion gases [16,17]. Carbon monoxide is produced during the combustion process; it is eventually oxidized to carbon dioxide (CO_2).

This is evidence of the thermal NO_X formation mechanism. Then NO concentration remains constant along the gas path. The analysis showed neither NO formation nor its consequent de-oxidation to form N_2 at the bottom of the flame.

Therefore, a decrease in NO concentration is due to a decrease in the oxidizing agent in the post-flame zone of NO_X formation. NO only forms if the temperature is above 1800 K [3]. In the maximum temperature zone due to great thermal energy dissociation of CO_2 [12] occurs as well as CO oxidation:

$$CO_2 + O \rightleftarrows CO + O_2 \tag{5}$$

The ratio of the direct reaction integral to the reverse reaction integral is 0.81 and 0.91 in the case of combustion with $\alpha = 1.05$ and 1.0 respectively. This is evidence that de-oxidation of CO_2 to form CO prevails over the oxidation reaction.

As the temperature of combustion products decreases, not enough energy becomes available for breaking apart bonds in CO_2 molecule, and now excess oxygen takes part in further oxidation of CO.

In case of combustion with excess air $\alpha = 1.0$ all free oxygen is consumed during combustion chain reactions. In the high temperature zone two processes occur simultaneously: oxidation of CO that has been produced as a result of de-oxidation of CO_2 and formation of nitrogen monoxide. Both of them involve oxygen consumption. A lot of oxygen is consumed to oxidize CO due to its higher reaction rate.

When α decreases from 1.05 to 1.0 the local peak value for O_2 concentration in the high temperature zone is reduced to one fourth. As has been mentioned, free oxygen in this zone is consumed in both NO formation and further oxidation of CO occurring at a high rate. All this results in the decrease of oxygen taking part in the formation of nitrogen monoxide and, therefore, in the suppression of NO emission when α decreases.

Results of the numerical experiment show that for natural gas combustion maximum concentration of NO is reached in case of combustion with excess air $\alpha_т = 1.05$. Reduction of α to 1.0 involves a NO decrease by 65% and further reduction of α to 0.95 and then to 0.9; this results in a decrease in NO concentration to 10-2 mg/m^3.

However, the main problem of the excess air combustion with less than 1 is that high concentrations of CO ranging from 10000 to 20000 mg/m^3 are the evidence of the extremely deep chemical incomplete combustion of fuel, therefore, such combustion method cannot be recommended even with near-zero NO emission.

Further oxidation of CO to CO_2 in a gas pipe accounts for the difference in CO concentrations in combustion products at the furnace exit and in stack gases. It might be rather essential and tends to increase with reducing air supplied into a furnace.

The most practically significant combustion is one with such an excess air factor that CO concentration in stack gases falls within the range of concentration standards [8]. The results of the numerical experiment were compared with the experimental data for this CO range using the following formula:

$$\delta_{NO} = \frac{NO}{NO_0} \times 100\% \tag{6}$$

where δ_{NO} – relative NO_X emission, NO – current NO_X concentration, NO_0 – NO_X concentration value for conventional combustion.

The 300 mg/m^3 CO limit [8] is reached when α decreases to 0.998 which means the fuel combustion process with near-stoichiometric excess air factor. However, this conclusion is true under the condition of the ideal mixing in the combustion zone. In reality, the amount of air supplied to a furnace always exceeds 1.0 for CO concentration in stack gases; so it is logical that the better fuel and air are premixed the higher NO_X suppression efficiency achieved for moderate chemical incomplete combustion of fuel.

The fact that the sum of the absolute values of the integrals for the reactions involving NO formation decreases (Figure 1) when α shows the suppression of NO due to a decrease in free oxygen in the combustion zone.

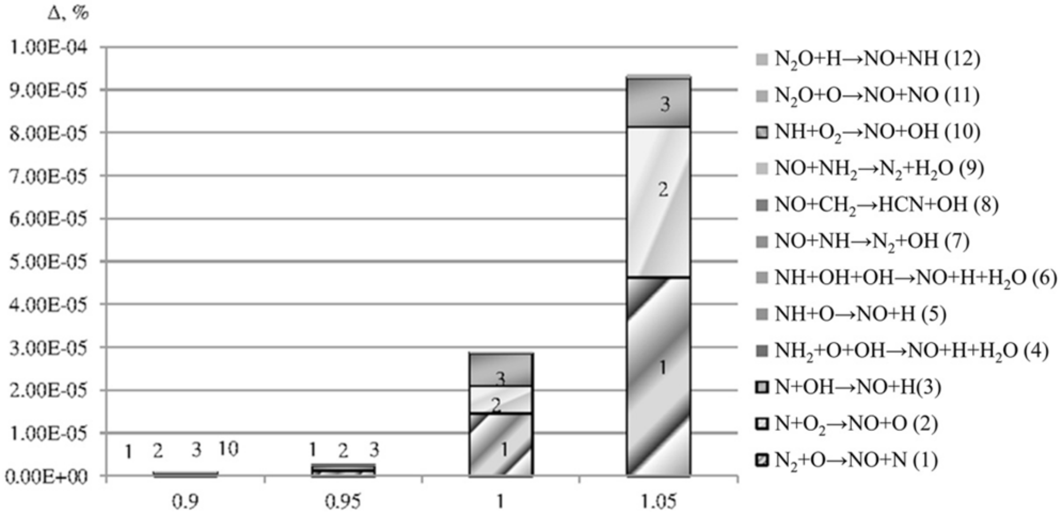

Figure 1. Absolute values of the integrals for the reactions involving NO formation.

Results of the relative contribution of 24 possible reactions of NO formation and consumption show (Figure 2) that NO mostly forms by the extended Zeldovich mechanism.

Such a situation occurs in the case of both conventional combustion and chemical incomplete combustion of fuel with $\alpha < 1$. Only in case of high oxygen deficiency, NO_X contribution grows (reaction 10 in Figure 2) due to a decrease in the value of the total integral for NO formation reactions. An increase in the relative contribution of the reaction $N + OH \rightarrow NO + H$ (reaction 3 in Figure 2) to NO_X formation when α decreases is due to hydroxyl OH involvement in the oxidation process; its reduction in concentration in the high temperature zone is not proportionate to reduction in oxygen concentration.

The numerical experiments show that the sum of the integrals for NO formation reactions becomes 3.25 times smaller when α decreases from 1.05 to 1.0, while the sum of the integrals for NO consumption reactions becomes 2.8 times smaller. To assess the change in the formation of a single substance, we should use the ratio of the differences between total integrals for formation reactions to the differences between total integrals for consumption reactions for the given substance. For NO, when α decreases from 1.05 to 1.0, it becomes 3.3 times smaller. Therefore, a decrease in NO formation is due to the loss of speed of conventional reactions of the extended Zeldovich mechanism. No significant de-oxidation of NO to N_2 in case of a decrease in the amount of air and flame enrichment is observed.

For consistent assessment of the overall efficiency of the given combustion method it was necessary to work out criteria for optimal conditions for its implementation. They are given below:

- total toxicity assessment for combustion products;
- boiler plant efficiency;
- plant operating costs;
- boiler reliability.

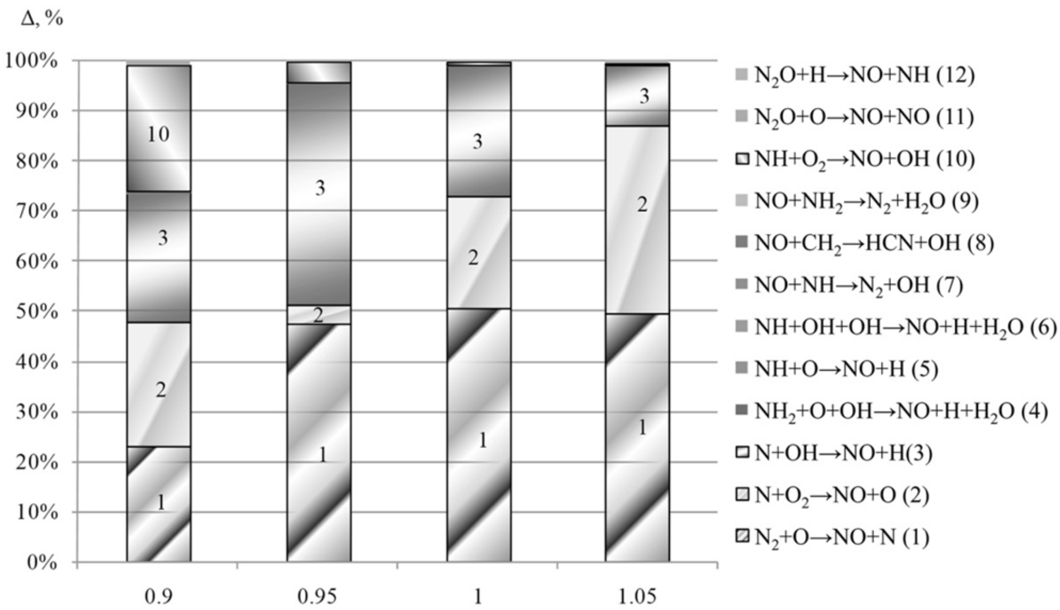

Figure 2. The relative contribution of integrals of chemical reactions to NO formation.

4. Boiler efficiency analysis

Boiler plant efficiency is obviously one of the efficiency assessment criteria for any combustion method. Reduction in both excess air and total toxicity index is accompanied by a reduction in heat leakage with stack gases q_2 and an increase in heat loss in case of chemical q_3 or mechanical q_4 incomplete combustion. By changes in the losses we can judge changes in boiler plant efficiency and fuel consumption.

Calculations of losses for chemical incomplete combustion (q_3, %) were performed using [10,18]:

$$q_3 = \frac{12640 \times \left(V_g + \left(\alpha_{xy} - 1\right)\right) \times C_{CO} \times 10^{-6}}{Q_p \times R} \times 100\% \quad (7)$$

where 12640 – the heat of combustion of CO, kJ/m^3; V_g, V_a – volumes of dry combustion products and air respectively, m^3/kg (m^3) (under standard conditions); C_{CO} – CO concentration in stack gases, ppm; Q_p – available heat, kJ/kg or 1 m^3 of fuel $Q_p = Q_i^r + Q_{ea} + i_{hf}$, Q_i^r – low heat value, kJ/kg (m^3), Q_{ea} – the heat input from preheated (combustion) air, kJ/kg (m^3); i_{hf} – sensible heat of the fuel, kJ/kg (m^3). R – heat loss due to chemical incomplete combustion coefficient related with CO content in combustion products: for solid fuel $R = 1$; for gas $R = 0.5$; for liquid fuel $R = 0.65$. Chemical incomplete combustion losses are calculated by (7) rather than directly due to the complexity of measurements of incomplete combustion by-products of fuel. In accordance with formula (7), heat loss due to CO incomplete combustion is only 50% of q_3.

Research results for different boilers show that chemical incomplete combustion losses of 0.04-0.06% (Figure 3), (with) CO concentrations in stack gases ranging from 50 to 100 mg/m^3, correspond to the minimum of the sum $\left(q_2 + q_3\right)$.

The experiments show that when α decreases to some values increase in chemical incomplete combustion losses is less than the decrease in losses with stack gases. Therefore, minimum total loss of heat with stack gases and chemical incomplete combustion, and consequently minimal fuel consumption per boiler, is observed in a reduced excess air area in case of moderate chemical incomplete combustion of fuel when CO concentration in stack gases does not exceed 100 mg/m^3.

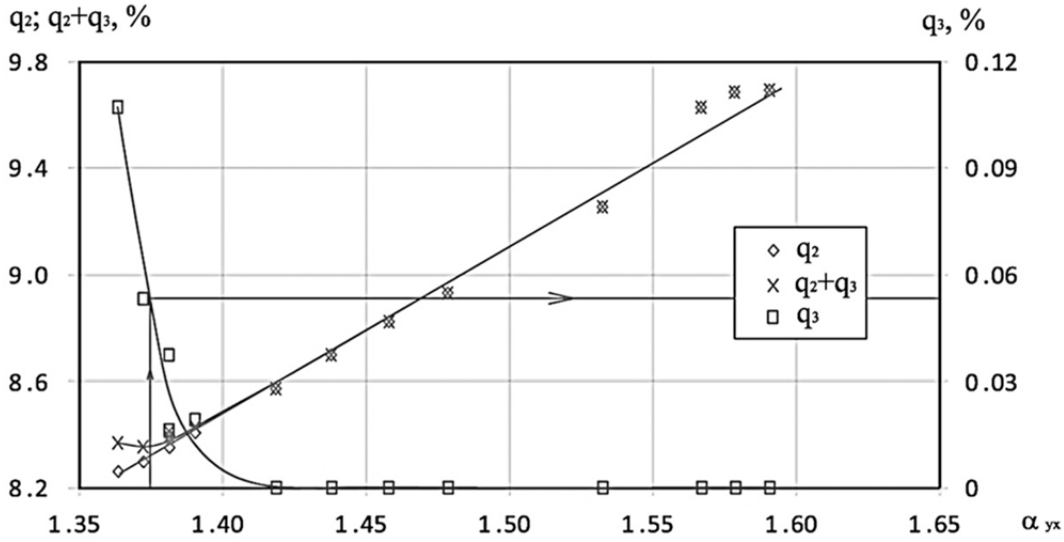

Figure 3. Excess air factor dependence of exhaust-gas-loss-q_2 and chemical incomplete combustion-loss-q_3 for boiler E-75-3.9 in the case of fuel oil combustion, D = 76-77 t/hr.

Hereinafter, we'll refer to the excess air that corresponds to the minimum total loss of heat with stack gases and chemical incomplete combustion as effective excess air α_{ef}.

Analysis of change in boiler efficiency based on experimental data, e.g. for boiler KVGM-180-150 shows that boiler efficiency increases up to its maximum value in the case of $\alpha_{ef.}$ when excess air factor decreases. If α decreases further, below α_{ef}, a fairly sharp drop in boiler efficiency, which is proportional to an increase in the concentration of chemical incomplete combustion by-products, is observed.

Dependence of boiler efficiency on CO concentrations in stack gases in moderate incomplete combustion area within the limits specified by State Standard GOST R 50831-95 (CO ≤ 300 mg/m^3) [8] is much weaker than on a change in excess air factor, especially for values less than $\alpha_{ef.}$.

Calculations performed on basis of experimental results show that consumption associated with boiler draft/draught strongly depends on draft fan actuator performance and ranges from 0.2-0.8% to 2% depending on load and combustion conditions (mode). Reduction in consumption associated with boiler draft/draught ranges from 0.01-0.03% to 0.05% respectively.

Practical research shows that the total toxicity index of combustion by-products steadily decreases when CO concentrations increase within the range 300-400 mg/m^3. However, maximum boiler efficiency is reached at lower CO concentrations, from 50 to 100 mg/m^3, with excess air α_{ef}.

In this connection, it is necessary to determine such a criterion for optimum moderate incomplete combustion conditions that would include environmental safety and boiler efficiency. One such criterion is plant operating costs.

Comparing results for different boilers [4,5,9,10,19] it is safe to assume that efficiency maximums and minimums of total operating costs occur at practically equal excess air factors and chemical incomplete combustion values that are characterized by CO concentration (in stack gases) ranging from 50 to 100 mg/m^3 in case of natural gas combustion due to the fact that annual payment for air pollution emissions (under existing standards) does not exceed 0.02% of total annual operating costs.

That is why boiler efficiency is the principal criterion for determining optimal conditions for moderate incomplete combustion of natural gas, taking into account current fuel prices and emission charges. Optimal excess air α_{opt}, as far as boiler environmental compatibility and efficiency are concerned, coincides with excess air α_{ef} that corresponds to maximum boiler efficiency. For boilers researched, emissions and fuel-cost savings range from 0.5 million rubles to 2 million rubles per 100 t/hr (of boiler steam capacity) a year in the case of natural gas combustion.

To analyze the influence of emission costs on the choice of optimal conditions for moderate incomplete combustion we performed calculations of total annual operating costs for different alternative tests.

The numerical results show that it is only when emission costs increase a hundredfold the curve becomes flattered near its minimum, and the minimum itself shifts to where CO concentration in stack gases is higher and ranges from 100 to 200 mg/m^3. In that case, total annual emission costs are about 2% of total annual operating costs S_Σ.

Therefore, the principal criterion for determining optimal conditions for moderate incomplete combustion should be reaching maximum boiler efficiency [20,21].

A possible increase in fuel prices, which involves a further increase in the contribution of fuel price to total operating costs, also supports the criterion selected. Research shows that efficiency behavior (as far as the dependence of efficiency on excess air and CO is concerned) is the same for every type of fuel. Therefore, the results obtained for natural gas combustion should be also true for both liquid fuel combustion and solid fuel combustion.

Therefore, for optimal boiler performance it is necessary that CO concentration in stack gases remains at the level that corresponds to its maximum efficiency.

The need to maintain CO concentrations within the given short range, lower than standard values for moderate incomplete combustion, to ensure optimal boiler performance, requires running continuous monitoring of NO_X, CO and O_2 concentrations in combustion products. This is why this method of NO_X reduction is called controlled chemical incomplete combustion of fuel.

Our research resulted in finding the range of CO concentrations in stack gases with a slight deviation of boiler efficiency from its maximum (within 0.05%). It ranges from 25 to 200 mg/m^3 depending on fuel type (Figure 4).

We used the change in gas temperature along the gas path as well as the temperature of the heating surface pipe wall to evaluate boiler reliability for moderate incomplete combustion.

Results of temperature tests for screen pipe walls and convection bank of boiler E-500-13.8-560 in case of moderate incomplete combustion of natural gas, represented in Figure 5, show that when α decreases tube temperature remains practically the same. Therefore, boiler surface reliability does not decrease in case of moderate incomplete combustion.

During experiments run for boiler E-480-13.8-560, a skewed fuel/air ratio was observed on the left (A) and the right (B) sides of the boiler due to uneven fuel and air delivery to burners on its left and right sides (Figure 6).

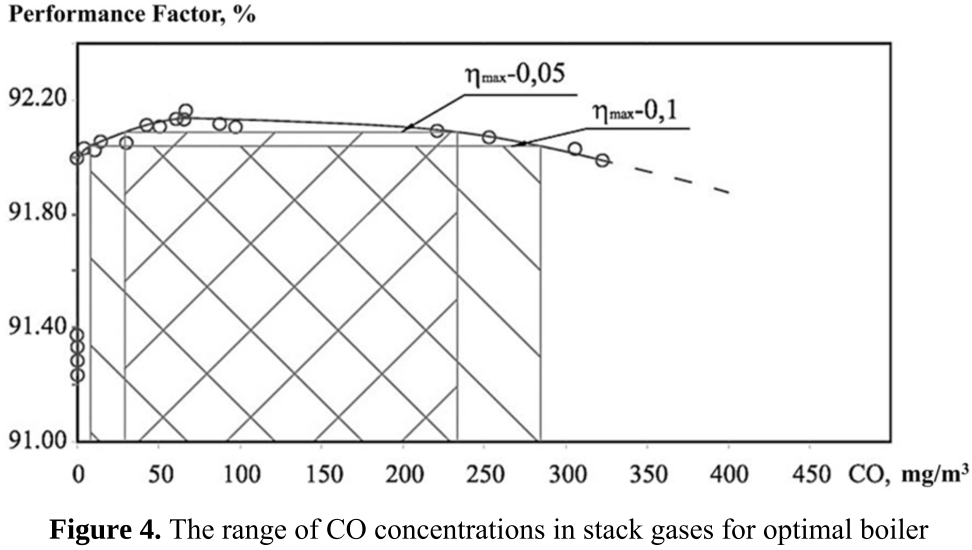

Figure 4. The range of CO concentrations in stack gases for optimal boiler performance: boiler E-75-3.9, natural gas combustion, $D = 75$ t/hr .

Skewed fuel/air ratio results in a decrease in boiler efficiency. Even fuel and air delivery to burners would allow us to decrease the amount of air supplied to the furnace and, therefore, to further reduce losses with stack gases q_2 and to increase both gross efficiency and a net efficiency of the boiler.

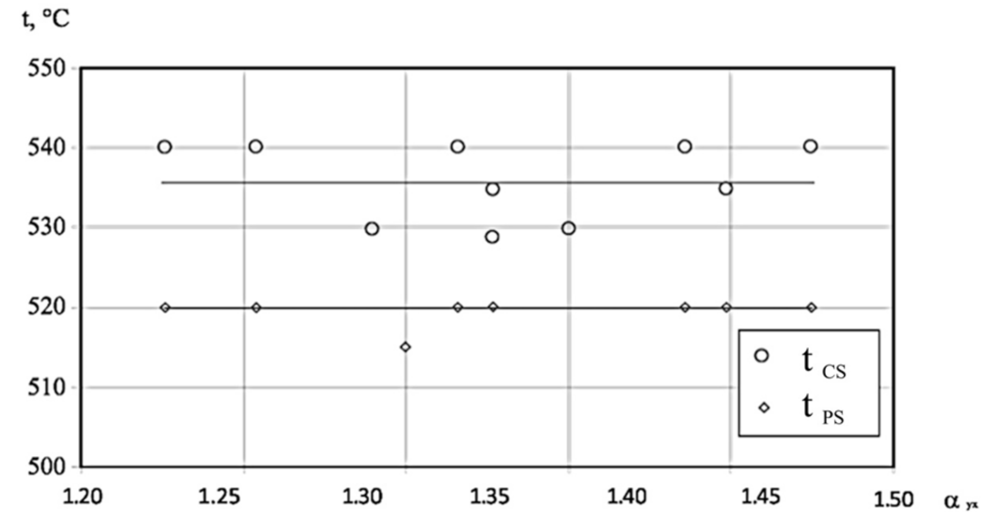

Figure 5. Dependence of platen superheater and convection superheater tube temperatures from excess air factor in stack gases: boiler E-500-13.8-560, natural gas combustion, $D = 370 - 410$ t/hr .

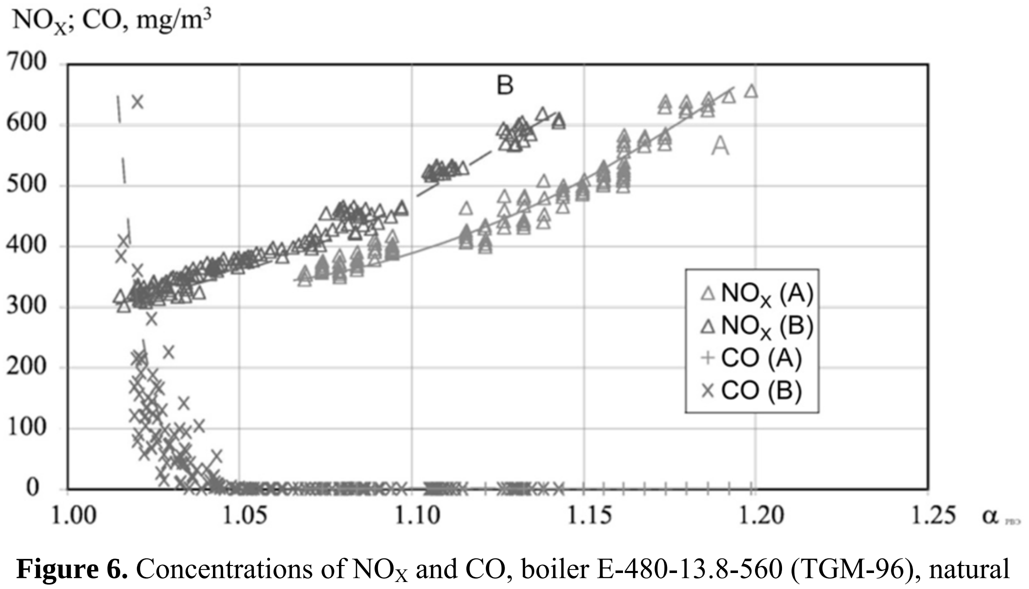

Figure 6. Concentrations of NO_X and CO, boiler E-480-13.8-560 (TGM-96), natural gas combustion, $D = 485$ t/hr : A – left side; B – right side.

That's why de-skewing should be performed, along with sealing the furnace and inspection of (standard) instruments, before adopting controlled moderate Incomplete Combustion technology, which allows us to optimize the combustion process and reduce CO-BaP yield. Then, functional performance testing should be conducted to determine 1) critical values α_{cr}, 2) allowable working values α_{add}, and 3) optimum α_{opt} excess air at different boiler loads, and regime maps for boilers should be worked out. CO concentration is strongly dependent on excess air during fuel combustion and can change dramatically with a slight change in α. This is due to the fact that CO concentration in stack gases might increase from 0 to 300-500 mg/m^3 and exceed CO concentration limits recommended for moderate incomplete combustion of fuel in case of change in excess air factor of 0.03-0.05. Therefore, when adopting controlled chemical incomplete combustion technology and working out a regime map for the boiler without a system for continuous monitoring of combustion product components, fuel has to be burned with near-critical (α_{cr}) excess air. This will provide air excess (supplied to the furnace) and guarantee proper boiler operation in a moderate incomplete combustion zone with CO concentration in stack gases that does not exceed 50 mg/m^3, which will allow us to improve environmental and economic indexes for boiler operation but will not provide maximum effect from adopting controlled incomplete combustion. Without continuous CO monitoring in combustion by-products, this is the only way to secure a boiler against large incomplete combustion in case of which it will not operate efficiently.

Fuel consumption and plant operating costs start increasing in case of moderate incomplete combustion with excess air less than α_{opt} (CO concentration ranges within 300-400 mg/m^3). Therefore, it is necessary to control and maintain CO concentration in stack gases at levels of 50-100 mg/m^3 in case of natural gas combustion to insure maximum efficiency in boiler operations. It is possible with a system for continuous monitoring of the composition of the combustion products [10].

5. Conclusion

Experimental research shows 20-40% NO_X reduction potential for existing boilers depending on fuel type and operating conditions with CO concentration in stack gases lower than standard levels specified in GOST R 50831-95 [8] due to chemical incomplete combustion.

The above-described method of combustion was implemented and tested at subcritical boilers that had 75-500 t/hr of steam capacity for natural gas combustion and it proved to be efficient and reliable. We showed a possibility in principle for its implementation for both liquid and solid fuel.

Optimal conditions for implementing the proposed method are reached in case of moderate chemical incomplete combustion when CO concentration in stack gases ranges from 50 to 200 mg/m^3 depending on fuel type. And at the same time boiler efficiency reaches its maximum due to a reduction in exhaust gas heat losses (q_2) and increases by 0.5-1% compared to conventional combustion.

In spite of some increase in incomplete combustion products (CO up to 100-200 mg/m^3 and BaP up to 70-100 ng/m^3), the total toxicity of moderate incomplete combustion products becomes 1.3-2 times smaller due to a noticeable reduction in NO_X emission.

Theoretical and numerical research showed that NO_X reduction resulted from the suppression of thermal NO_X formation by the extended Zeldovich mechanism. Maximum reduction in NO_X emission reached 65% for ideal mixing in the case of natural gas combustion.

Practical guidelines for implementation of the proposed method with existing boilers (steam capacity up to 500 t/hr) were developed as a result of the analysis of experimental data for combustion of different types of fuel.

References

[1] Zhang Y, Tao S 2009 Global atmospheric emission inventory of polycyclic aromatic hydrocarbons (PAHs) for 2004 *Atmos. Environ.* **43** 812–819

[2] Kim K H, Jahan S A, Kabir E, Brown R J 2013 A review of airborne polycyclic aromatic hydrocarbons (PAHs) and their human health effects *Environ. Int.* **60** 71–80

[3] Oluwatoyin K, Oluwasegun A, Alabi A 2015 Modernization Technologies of Existing Thermal Power Plants in Nigeria *Journal of Scientific Research and Reports* **8** 1–8

[4] Roslyakov P V, Pleshanov K A, Ionkin I L 2011 Fuel combustion with monitored moderate under burning *Annals of DAAAM 2011 & Proceedings of the 22nd Int. DAAAM Symposium* **22(1)** 1153–1154

[5] Sarunac N, Romero C E, Levy E K, Weston W C 2001 Anatomy of a successful combustion optimization project *The proceedings of the MEGA symposium. Air & Waste Management Association*

[6] Wang J, Zhang W, Cao R, Xiangyu Y Lai H 2016 Analysis of Nitrogen Dioxide in Environment *Advances in Bioscience and Biotechnology* **07** 278–288
[7] Suchkov S, Kotler V, Batorshin V 2016 Effective ways to modernize outdated coal heat power plants *Thermal Engineering* **63** 852–862
[8] GOST R 50831-95. Boiler plants. Heat-mechanical equipment. General technical requirements (in Russian)
[9] Roslyakov P V, Ionkin I L, Pleshanov K A 2010 The optimal conditions for firing fuel with controlled incomplete combustion *Thermal Engineering* **4** 290–295
[10] Roslyakov P V, Ionkin I L, Pleshanov K A 2009 Efficient fuel firing with controlled incomplete combustion *Thermal Engineering* **1** 20–23
[11] Klyushenkova M I, Lukanin A V 2021 Protecting the environment from industrial air emissions (Moscow: Infra-M) p 142 (in Russian)
[12] Roslyakov P V, Egorov L E, Burkova A V 1993 Mathematical Modeling and Calculation of Toxic Combustion Products Emissions of Organic Fuels *Thermal Engineering* **7** 63–68
[13] Supranov V M, Ryabov G A, Melnikov D A 2010 Studying The Possibility And Expediency Of Transferring BKZ-420-140-NGM Boilers to Oxy-Fuel Combustion *Thermal Engineering* **4** 23–27
[14] Kenbar A M A, Beltagui S A, Ralston T, MacCallum N R L 1993 Measurement and Modelling of NO_X Formation in a Gas Fired Furnace *Combustion Science and Technology* **93(1)** 173–192. doi:10.1080/00102209308935288
[15] Zhang Y Ji S, Wang R, Qi G 2020 Study on combustion and nitrogen oxide emissions of gas boiler *IOP Conf. Ser.: Mater. Sci. Eng.* **721** 012054
[16] Best Available Techniques (BAT) Reference Document for Large Combustion Plants EUR 28836 EN 2017 https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/JRC_107769_LCPBref_2017.pdf
[17] Volchkov É, Dvornikov N 2006 Modeling of incomplete combustion of hydrocarbons in the presence of water under high pressure *Combustion Explosion and Shock Waves* **42** 277–281
[18] Suchkov S, Kotler V, Batorshin V 2016 Effective ways to modernize outdated coal heat power plants *Thermal Engineering* **63** 852–862
[19] Dzikuć M, Piotr K Dudziak R, Szufa S, Dzikuć M Godzisz K 2020 Selected Aspects of Combustion Optimization of Coal in Power Plants *Energies* **19** 2208
[20] He B, Heal M, Reis S 2020 Modelling public health benefits of various emission control options to reduce NO_2 concentrations in Guangzhou *Environmental Research Communications* **2.** doi:10.1088/2515-7620/ab9dbd.
[21] Jerzak W 2015 Emissions of NO_x and CO from Natural Gas Combustion with Adding CO_2 at Varying Distances from the Burner *Rocznik Ochrona Srodowiska* **16** 148–160