Environmental and economic evaluation of selective non-catalytic reduction of nitrogen oxides

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Abstract. There are two groups of atmosphere protecting measures: technology (primary) and treatment (secondary). When burning high-calorie low-volatile brands of coals in the furnaces with liquid slag removal to achieve emission standards required joint use of these two methods, for example, staged combustion and selective non-catalytic reduction recovery (SNCR). For the economically intelligent combination of these two methods it is necessary to have information not only about the environmental performance of each method, but also the operating costs per unit of reduced emission. The authors of this report are made an environmental-economic analysis of SNCR on boiler II-50P Kashirskaya power station. The obtained results about the dependence of costs from the load of the boiler and the mass emissions of nitrogen oxides then approximates into empirical formulas, is named as environmental and economic characteristics, which is suitable for downloading into controllers and other control devices for subsequent implementation of optimal control of emissions to ensure compliance with environmental regulations at the lowest cost at any load of the boiler.

1. Introduction
Nitrogen oxides are formed during combustion of all fuels, so the fight against them is the main task of the environmental services of thermal power plants. To reduce the concentration of nitrogen oxides in flue gases of power boilers used two groups of measures: technology (primary) and treatment (secondary). When burning high-calorie "skinny" coal, for example, Kuznetsk T grade, anthracite, which are used by power plants in the European part of the Russian Federation, for better ignition of the fuel used the furnaces with liquid slag removal. In this case, there is a particularly high concentration of nitrogen oxides in the flue gas at the exit of the furnace as the high temperature in the combustion zone contributes to the generation of "thermal" nitrogen oxides formed by oxidation of nitrogen in the air. To reduce the concentration of nitrogen oxides to the set standards in this case, you need to use multiple denitration events. Aggregate environmental-economic indicators as the best available technologies may be selected fuel staged combustion (SC) (primary method) and selective non-catalytic reduction recovery (SNCR) of nitrogen oxides (secondary method). This combined two-stage system of nitrogen oxides suppression installed and tested at the two-furnace supercritical once-through boiler II-50P of the 330 MW power unit of Kashirskaya GRES [1].

Without the use of denitration measures concentration of nitrogen oxides is 1400 mg/m³. With the help of technological measures (SC) it can be reduced to 800 mg/m³. In accordance with GOST R 50831-95 for boilers of this type the standard allowable concentration of nitrogen oxides is 570 mg/m³ at nominal load.
All measures to reduce emissions of nitrogen oxides require additional costs. A feature of the operation of thermal power plants is to work with variable load. In the absence of denitration measures the concentration of nitrogen oxides in flue gases of boilers is directly proportional to the load, and mass ejection is proportional to the square of the load. It follows that the emissions of nitrogen oxides need to manage, increasing the degree of input denitration effects with increasing load and decreasing with its reduction in order to reduce the baseless economic losses.

For the economically competent management of emissions it is necessary to have special characteristics (mathematical models) of equipment, which connects the load of the boiler (D) massive release of harmful substances (m), a quantitative indicator of the degree entering the atmosphere protecting effects (for nitrogen oxides it are \( r \) - degree of recirculation of flue gases, \( \beta \) - degree of SC, \( k \) - the supply of a reagent such as urea) and the cost of this denitration measure (Z). Such ecological and economic characteristics (EEC) can evaluate a method of abatement in a particular environmental contaminant (SC, SNCR, etc.) or work of equipment that is generating (boiler) or intercepting (filter) some kind of pollutant. For example, for the staged combustion of fuel EEC will be of the form \( Z(D, m) \) or \( Z(D, \beta) \), for SNCR - \( Z(D, m) \) or \( Z(D, k) \). EEC representation in the form \( Z(D, m) \) shows what price is supported the emission \( m \) at the load \( D \), that allows at the design stage to reasonably choose the most economical options, and in the process of operation is to select the optimal modes of operation. For example, to distribute the total emissions set for the TPP among the power units. EEC representation in the form \( Z(D, \beta) \) or \( Z(D, k) \) is convenient for operational management [2], when it is necessary reasonably select and maintain on the object the denitration values \( \beta \) and \( k \).

At a certain load \( D \) the parameters \( m \) and \( \beta \), \( m \) and \( k \) uniquely, functionally linked. Having the EEC of SC and SNCR the emissions control system may at any load of the boiler to maintain the optimum values of \( \beta^* \) and \( k^* \), providing emission-level standard at a minimum total cost of the SC and SNCR.

2. Data sources for creating EEC

EEC is a data-intensive description, which combines three entities: energy, economy, ecology. It is designed for optimal control of emissions, but management decisions, excluding at least one of these three factors will not be optimal. In the Russian conditions they often neglect the economy, it is a historical legacy of the competition-free Soviet planned system, still sitting in the minds of many business leaders and even scientists. To build EEC must have a fairly large amount of initial information about the technology of the functioning of the installation, construction of equipment, values of key parameters in the working range of the load, resource and energy consumption and their cost at the time of calculation. Some of the most important information is obtained experimentally, for example the dependence of the concentration of nitrogen oxides to the degree of gradation (\( \beta \)) of fuel staged combustion, the other by calculation, if the calculation satisfy the accuracy requirements. When the calculation of costs were used prices (fuel, electricity, heat, urea) of 2012.

In the composition EEC used only the operational (current) costs associated with operation of the SNCR, and only the portion that varies with changes in atmosphere protecting actions, which adopted the consumption of the reagent (urea) \( k \). Semi-fixed costs such as depreciation of equipment, salaries of staff etc. were not considered. This is due to the fact that EEC is designed for operational supply control of the urea, therefore, should take into account only those components of the total costs that change when \( k \) changes, i.e. "feel" this parameter. Accounting of fixed cost will not change the value of the optimal emission \( m^* \) (or \( k^* \)), it will take place simply at higher costs [3]. Therefore, in accordance with the known principle of "Occam's razor", all the unnecessary should be discarded. (An exception was made only in respect of the cost of steam supplied to the mixers and distribution grid, the consumption of which does not depend on the load or from the supply of the reagent, due to the relatively large share of the steam cost in the total cost).

For the simplification of EEC using the costs are measured in RUB/h, steam load of the boiler in t/h, the emissions of oxides of nitrogen in g/s, the supply of urea in g/s.
Technology of SNCR based on the selective interaction of nitrogen oxides with the products of thermal decomposition of urea in the gas phase at a temperature of 850-1050 °C. In the resulting view, the reaction of nitrogen oxides reduction by urea is expressed by the equation:

\[ 2\text{CO(NH}_2\text{)}_2 + 4\text{NO} + \text{O}_2 = 4\text{N}_2 + 2\text{CO}_2 + 4\text{H}_2\text{O} \]  

The stoichiometric equation (1) shows that the recovery of 1 kg of nitrogen monoxide requires the same amount of urea. But in practice, urea need to apply a bit more to compensate for the nonideal mixing of the reagent with the flue gases in the reaction zone. At the same time in the flue gas remains a portion of unreacted ammonia, "slip" with a concentration of not exceeding the standard of 20 mg/m³.

In figure 1 is a flow diagram of SNCR for unit No. 3 of Kashira TPP [1]. Granular urea pneumatically loads into the storage hopper of solid urea 1, from which by a screw feeder 2 is fed into the tank preparation of the solution 3, which also receives chemically purified water, heated by heating water system from 10 to 55 °C in heat exchanger 4. Compressed air from the compressor 5 is fed to the tank 3 and the hopper 1. 40% solution from tank 3 by pump 6 through the filter 7 is fed into the feed tank 8, where the pump 9 is supplied to the mixers 10 and 11 on each of the casings of the twin-furnace boiler. In mixers the solution is mixed with superheated steam at a pressure of 2 MPa. At temperatures over 250 °C, the urea decomposes into ammonia and other components. Next, the vapor-gas recovery mixture is injected into the flue gas stream via the distribution grids 12 and 13, placed in the horizontal flue between the banks of platen superheater.

Table 1 shows the prices of materials and energy (in rubles at the exchange rate of 2012) are spent by SNCR in the process.

### Table 1. Prices for materials and energy consumed by SNCR.

| Component                  | Unit   | Price per unit, RUB |
|----------------------------|--------|---------------------|
| Urea dry, granular         | 1 t    | 12000               |
| Water chemically purified  | 1 t    | 40                  |
| Steam, pressure 1.3 – 2.0 MPa | 1 t  | 185                 |
| Electricity                | 1 kWh  | 1.50                |
| Thermal energy             | 1 Gcal | 500                 |

3. Development procedure of the EEC

The development of the EEC consists of the following steps:
• The choice arrays of the discrete values of the boiler load D and denitration impact (consumption of urea) k for the following calculation.
• Calculation the SNCR costs Z for selected values of k and D. Obtaining the matrix of values the function of two variables Z(k, D).
• Calculation the mass emissions of nitrogen oxides m for the same values of k and D. Receiving matrix of the function values m(k, D).
• Combine the arrays Z(k, D) and m(k, D) with the exception parameter k and receiving the array of discrete values EEC Z(m, D).
• Approximation the table of Z(m, D) to obtain analytic function (empirical formula) EEC in the form that easy to download in the controllers and other digital devices to use for control.

3.1. The choice arrays of values D and k.
As a design points of the boiler load D were selected the following values in the range from 70 to 100% of nominal: 735, 810, 890, 950, 1050 t/h; feed urea k: 0, 20, 40, 60, 80, 100, 120, 140, 160, 180 g/s.

3.2. Operating costs for SNCR.
Table 2 presents a part of results the operating costs calculation: the structure of costs at nominal load and urea supply 175 g/s (630 kg/h). It should be noted that the overwhelming proportion of operating costs (99.4%) have two components: the costs of urea and steam.

Table 2. Structure of operating costs for SNCR.

| Components of the costs                        | Cost, RUB/h | Fraction of total, % |
|------------------------------------------------|-------------|----------------------|
| Urea                                          | 7560        | 71.46                |
| Steam, pressure 1,3 – 2,0 MPa                 | 2956        | 27.94                |
| Water, chemically purified                    | 37.61       | 0.36                 |
| Heat on the water heating                     | 21.22       | 0.20                 |
| Electricity                                   | 3.89        | 0.04                 |
| Sum                                           | 10579       | 100.00               |

3.3. Mass emissions of nitrogen oxides
Mass emissions of nitrogen oxides at the outlet zone of SNCR was calculated as the product of the nitrogen oxides concentration (depending on the load of the boiler and the feed of urea) on the amount of flue gas (depending on load). The volume of flue gas was adjusted to the volume of dry gas at normal conditions and the excess air coefficient α = 1.4. Taking into account that the supplied to the reaction zone, the urea breaks down into two parts: k = k1 + k2, where k1 is the bulk of the reagent is consumed for neutralization of nitrogen oxides; k2 – part of reagent consumed in the creation of excess ammonia (slip) in a concentration of 15 mg/m³. When the calculation took into account that the concentration of nitrogen oxides at the inlet area of the SNCR at rated load is 800 mg/m³.

3.4. Representation of EEC
In figure 2 gives a graphic representation of EEC SNCR as the dependence of operating costs Z of the mass emission of nitrogen oxides m for different values of boiler load D. Geometrically EEC represents a surface in the space Z, m and D. To use the EEC for the optimization calculations, for loading into the memory of digital control devices (controllers, blocks of hardware complexes), it is necessary its analytical representation as a formula. This is most simply to accomplish with the
approximation of calculated tabular data (a vector of values $D$ and matrix of values $m$ and $Z$). The result is the empirical formula containing 6 constant coefficients $a_1$, $a_2$, $a_3$, $b_1$, $b_2$ and $b_3$, the values of which depend on the nature of the relationship between $Z$, $D$ and $m$ and the dimensions of these parameters:

$$Z(m, D) = a_1 + a_2 \cdot D + a_3 \cdot D^2 + (b_1 + b_2 \cdot D + b_3 \cdot D^2) \cdot m.$$  \hspace{1cm} (2)

EEC SNCR, presented in the form (1), (let's call it “option 1”) is tied hard to the values of the emission $m$, that in many cases complicates its use in process optimal control emissions of nitrogen oxides. When using SNCR in the second stage of nitrogen oxides suppression (and this is its main use in power boilers), it is more convenient mobile version of EEC, in the analytical model (2) of which the absolute value $m$ is substituted for $\Delta m$ – the value of reducing emissions as a result of SNCR work (option 2). In this case, the range of costs and the structure of the approximating formulas (2) remain the same, but the coefficients $a_1...b_3$ change. In figure 3 shows the EEC variant 2.

### 3.5. The use of EEC SNCR

Figure 4 illustrates the application of EEC for optimal control of nitrogen oxides emissions when used together the SC and SNCR at a nominal load. Mass ejection is reduced from $m_0$ (corresponding to emission when the concentration of nitrogen oxides $C_0 = 1400$ mg/m$^3$ in the absence of denitration measures) to $m_2$ corresponding to the standard value of concentration $C_2 = 570$ mg/m$^3$, by the consecutive application of processes 1 (SC) and 2 (SNCR). The values of $m_0$ and $m_2$ depend on the load of the boiler, decreasing with decreasing load. SNCR is the "slave" process, its task is to reduce emissions by the amount $\Delta m = m_1 - m_2$, where $m_1$ is the emission at the output of SC (at the entrance to the zone of the
SNCR). In the overlap region 3, the emission reduction can be performed by using a SC and SNCR. The optimization problem is to find and hold the optimal values of emissions \( m_1^* \) at each load, that is corresponding the minimum total cost denitration measures when observance of the limitations \( m_{1\text{min}} \leq m_1 \leq m_{1\text{max}}, m_0 \) and \( m_2 \). Found optimal values of \( m_1^* \) translated to the optimal values denitration actions \( \beta^* \) and \( k^* \), which are transmitted as setpoints to local regulators of \( \beta \) and \( k \). There are three possible optimal mode:

- The optimal regime is on the line \( m_{1\text{min}} \), i.e. you need to "squeeze all" from the staged combustion. The "steepness" (or relative growth) EEC SNCR in the zone of overlap is greater than one for SC.
- The optimal regime is on the line \( m_{1\text{max}} \). The relative growth in the SC in zone of overlap more than one in the SNCR.
- Optimal mode lies within the zone of overlap at the point of equality relative gains.

The use of EEC SC and SNCR provides efficient method to solve this problem.

4. References

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