ANALYSIS OF NITROGEN OXIDES EMISSION REDUCTION AND CHANGES IN EXERGY BY FLUE GAS RECIRCULATION DURING NATURAL GAS COMBUSTION

***Luka M. MARINOVIĆ*[*1], Dejan M. MITROVIĆ*[1]**

[1]University of Niš, Faculty of Mechanical Engineering in Niš, Serbia

[*] Corresponding author; E-mail: l.marinoviclmm@gmail.com

With the development of the economy and society in the world, fuel consumption has increased, and thus the emission of pollutants into the environment. Since gaseous fuels represent the most environmentally friendly type of fossil fuel, the emission of nitrogen oxides, as the main pollutant during their combustion, is causing more and more research interest. This paper deals with the impact of recirculation of combustion products on the reduction of nitrogen oxide emissions, and exergy destruction as its consequence. In the first part of the paper, mechanisms of nitrogen oxides formation and the factors that affect it are reviewed. After that, a simplified analysis of the flue gases recirculation was performed especially its influence on emission reduction and exergy losses in flue gases stream. The results are discussed in last part of the paper. Presented results can be very useful for quick emission calculations in process of designing natural gas boiler plants.

Key words*: nitrogen oxides, emission reduction, combustion, flue gases recirculation, Zeldovich mechanism, natural gas, exergy*

1. Introduction

Combustion processes are always accompanied by the formation of combustion products that are released into the atmosphere. In addition to the primary combustion products, such as CO_2, H_2O, and others, lot of pollutants are also emitted. The main harmful elements of flue gases are nitrogen oxides (NO_x), carbon-monoxide (CO) sulfur dioxide (SO_2), particular matters and others. Some authors [1] also consider carbon dioxide as pollutant, but it is the unavoidable product of combustion, which can be eliminated only by shutting down furnaces and boilers, or eventually extracted from flue gases and stored somewhere in the Earth by Carbon Capture and Storage systems (CCS) [2]. Authors in numerous studies [3,4] pointed NO_x as the most harmfull pollutant in natural gas combustion products. As the natural gas is the cleanest fossil fuel, lot of efforts are being made for its emission reduction in gas boiler plants.

There are lot of measures for reduction of NO_x emission. They are divided in two big groups: primary also called technological measures which impact on combustion process, and NO_x production mechanisms, and secondary meassures which separate already formed NO_x from flue gases by chemical or physicochemical processes [1, 5-8]. Using low NO_x burners and rather cooling the flame by introducing some fluids in combustion chamber or upstream of the burner are often used primary measures for emission reduction. Jerzak W. [9] investigated adding of CO_2 at different distances from the burner in combustion zone. Navrodska et al. [10] considered influence of air humidifying by condensate from flue gases, with special heat recovery system, in cases of hot water and steam production. Lean combustion is also an effective reduction method, but achieving the desired emission values requires high excess air ratios, which reduces the efficiency of the plant [11]. One popular method in engineering practice, especially in district heating boiler plants is external flue gas recirculation (FGR), which can reduce emission of $\mathrm{NO_x}$ significantly below the values prescribed by regulations, with acceptable impact on plant efficiency [1,12]. Many authors have dealt with this concept of $\mathrm{NO_x}$ emission reduction. Tanasić et al. [3] experimentally investigated implementation of FGR in district heating plant boilers fired by natural gas. Abdelaal et al. [13] considered FGR in case of kerosene combustion in laboratory furnace with varying air quantity, and concluded that emission can be reduced more than 90% depending on value of excess air. Varga et al. [14] experimentally investigated influence of FGR on $\mathrm{NO_x}$ emission during the combustion of natural gas in low $\mathrm{NO_x}$ burner, by varying quantity of air, and reported that emission of $\mathrm{NO_x}$ decreases approximately 70-80%. In addition to external flue gas recirculation, internal flue gas recirculation in different versions can be also implemented for $\mathrm{NO_x}$ emission mitigation. It is more efficient in $\mathrm{NO_x}$ emission, because achieving similar reduction with smaller volume of flue gas, but it tends to contribute to occurrence of flame instability at low recirculation ratios [14-16]. An overview of other methods for reducing nitrogen oxide emissions is given in the papers [5,6]. Lot of FGR systems are implemented in old boiler plants to avoid installation of expensive low $\mathrm{NO_x}$ burners. District heating system of Faculty of Mechanical Engineering in Niš is example of good practice where this method achieves very good results and emission decrising from 119 mg/m^3 to 71.38 mg/m^3[12].

Even this method is the most implemented, literature in this field, especially one that can be applied in practical calculations is very deficient. All available papers and calculation results are based on very complex mathematical, usually numerical approach. Impact of FGR on exergy of flue gases is also unexplored, even it is very important aspect of combustion process. Due to this methodology is not explored enough, the point of this paper is to analyze the impact of external flue gas recirculation on nitrogen oxides formation during natural gas combustion process, and its contribution to exergy destruction of flue gases, by using simpler mathematical approach, with acceptable imprecision. Adiabatic combustion of natural gas of a given composition with implemented external FGR was considered, with certain simplifications.

2. Nitrogen oxides formation

There are two dominant oxides of nitrogen contained in flue gases: nitrogen monoxide (NO) and nitrogen dioxide ($\mathrm{NO_2}$), which are abbreviated noted as $\mathrm{NO_x}$. Emitted $\mathrm{NO_x}$ usually consists of 90-99% NO and 1-9% $\mathrm{NO_2}$, but as a rule NO in contact with air oxidize into $\mathrm{NO_2}$ [1,14,17,18]. Third species of nitrogen oxides, called nitrous oxide $\mathrm{N_2O}$, can occure in flue gases in case of fuel lean combustion at low temperatures and elevated preassures, but its lifetime in combustion products for temepratuers above 1500K is very short, and its presence in combustion products of natural gas combustion is negligible. Nitrogen oxides are the main harmful components of natural gas combustion products due to many reasons. $\mathrm{NO_x}$ emitted from combustion processes passes through a series of physicochemical reactions whose final products are nitric acid fog and nitrates. Under sunlight, nitrate combines with hydrocarbons and ozone to produce photochemical smog, which is hazardous to respiratory system and human health, and to increase acidity of rain. Nitrogen oxides, especially emitted from airplane transport has great impact on ozone removal in stratosphere [4,8].

The theory classifies NO_x formation mechanisms in three groups: Zeldovich (thermal) mechanism, prompt NO_x mechanisms, which are responsible for oxidation of molecular nitrogen from air ang gas fuel, and fuel NO_x mechanism. The last mechanism is important in the combustion of solid fuels and isn't important for further exposition of this paper. NO_2 formation mechanism is insignificant with exeption of combustion in gas turbine power plants [1,8].

Zeldovich mechanism of NO formation can be expressed by following equations [1,8]:

$$\mathrm{O} + \mathrm{N_2} \rightleftharpoons \mathrm{NO} + \mathrm{N} \tag{1}$$

$$\mathrm{N} + \mathrm{O_2} \rightleftharpoons \mathrm{NO} + \mathrm{O} \tag{2}$$

$$\mathrm{N} + \mathrm{OH} \rightleftharpoons \mathrm{NO} + \mathrm{H} \tag{3}$$

Precisely speaking, reactions (1) and (2) represent Zeldovich mechanism, and all three together represent extended Zeldovich mechanism. This mechanism has a very high activation energy, and take place only at high temperatures of combustion. At combustion temperatures lower than 1800 K this mechanism can be neglected [1].

Prompt mechanisms are related to the formation of the quantity of NO, which can not be explained by the thermal mechanism, due to much higher reaction rates. Currently, promt mechanisms are not sufficiently explored, and are described by several mechanisms. Usually, it occures in fuel-rich regions, when hydrocarbon radicals react with molecular nitrogen to form NO_x at high temperatures [14]. Each mechanism may have a greater or lesser impact on NO_x emission depending on the combustion conditions. The most famous prompt mechanism is Fenimore's mechanism, which obtain in fuel rich regions and at temperatures between 1200 and 1600K, when thermal mechanism does not occure [1].

Total NO_x production depends on a lot of parameters, but there are three main ones: maximum temeperature in some points within the furnace, the residence time of oxygen and nitrogen in regions with high temperature and oxygen concentration within occupied space by flame [3,17]. Depending on many factors, such as cinematics of flow, exess air coefficient, rate of combustion etc. contribution of each mechanism to NO_x formation can be great or less. In one study, contribution of some mechanisms was determined in laminar flame. In that case Zeldovich mechanism NO fraction in total NO amount is 50%, and Fenimore's mechanism fraction 10% (with residence time in high temperature zone 5ms) [8].

2.1. Influence of main parameters on nitrogen oxides formation

Flame temperature and residence time in the highest temperature zones contribute the most to the Zeldovich NO_x production. Impact of residence time is not that significant for NO formation as it is in case of NO_2 formation. It can be reduced by increasing the turbulence [14]. Temperature has profound influence on NO_x as it is shown in Fig. 1.

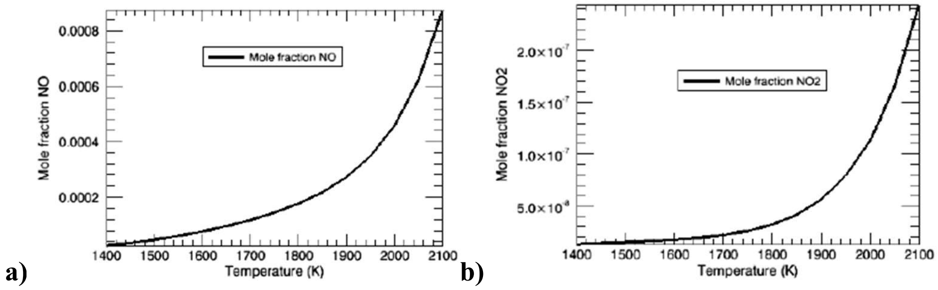

Figure 1. Calculated influence of temperature on: a) NO and b) NO_2 fraction products on natural gas combustion performed for a residence time of 1s [17]

This phenomenon occurs because the dominant formation mechanism Zeldovich mechanism, and some prompt mechanisms are strong dependent of combustion temperature. At temperatures below approximately 1500K, NO_x formation in gas fuels usually is negligible. Due to this dependence on temperature, measures to reduce the emission of nitrogen oxides are primarily aimed at reducing the combustion temperature through combustion process modifications. Form of the dependence of NO formation for other values of the residence time is similar to form shown in the Fig. 1 but with different values of mole fraction.

Decreasing oxygen concentration in fuel and oxidizer mixture (dilution of oxydizer) affects on NO_x production by reducing partial preassure of oxygen in combustion zone. Fig. 2 shows influence of this factor on NO_x production.

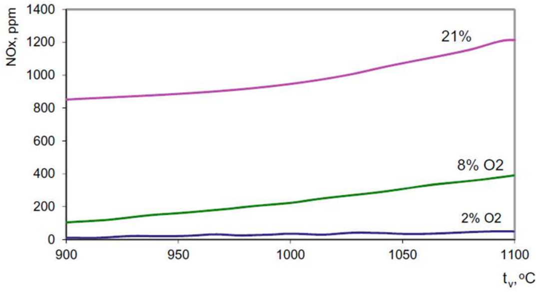

Figure 2. Influence of oxygen concentration and preheating temperature of air t_v on NO_x concentration in flue gases [3]

3. Flue gas recirculation for nitrogen oxides emission reduction

External flue gases recirculation (FGR) means extraction of flue gas from gas tract and injection at the point upstream of the extraction location. Extraction for NO_x emission reduction is usually performed from flue gases stream and injection is performed combustion air stream. The physical background of this method is reducing temperature peaks in the flame zone, by introducing flue gases which have higher heat capacity than combustion air, and absorb more heat with lower increasing of temperature. According to this fact, reactions of NO_x formation slows down, because of lowering the flame temperature [18,19]. The recirculation (FGR) coefficient is the main parameter of FGR:

$$x = \frac{V_{rec}}{V_{rw}^{r}} \tag{4}$$

where V_{rec} is volume of recirculated products, and V_{rw}^{r} is volume of total, wet combustion products per unit of fuel. The relation between and volume of total products without FGR V_{rw} is [19]:

$$V_{rw}^{r} = \frac{1}{1-x} V_{rw} \tag{5}$$

Quantity of released component of flue gas per unit of fuel V_i^r is, according to expression (5):

$$V_i^r = \frac{1}{1-x} V_i \tag{6}$$

If there is not air preheating and thermal dissociation, energy balance of adiabatic combustion process with FGR per unit of fuel can be expressed as:

$$\text{LHV} + x \cdot h_{rw}^{\text{r}}(T_{\text{ex}}) = h_{\text{cp}}(T_{\text{ad}}) = \sum V_i{}^r h_i(T_{\text{ad}}) \tag{7}$$

where LHV is lower heating value of the fuel, $h_{rw}^{r}(T_{\mathrm{ex}})$ is enthalpy of total combustion products on the extraction temperature T_{ex} and $h_{\mathrm{cp}}(T_{\mathrm{ad}})$ and $h_i(T_{\mathrm{ad}})$ are enthalpies of combustion products and each components on adiabatic combustion temperature T_{ad}, which is equivalent to theoretical furnace temperature in boiler desigh calculations. Depending on enthalpy expressions, combustion temperature is calculated from relation (7). This method also disrupts the formation of nitrogen oxides by reducing availability of oxygen in the flame zone, but with less contribution due to a small decreasing in oxygen concentration at usual values of x. Influence of FGR system on $\mathrm{NO_x}$ production in one case is shown in Fig. 3.

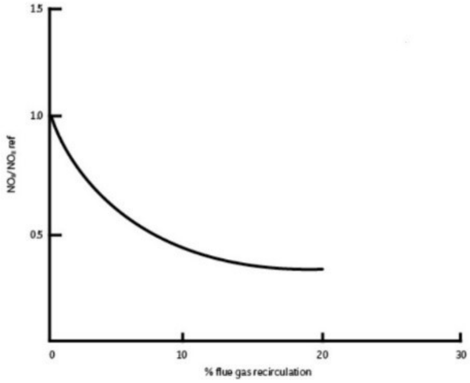

Figure 3. Influence of FGR on $\mathrm{NO_x}$ emission (dependance of relative emission of $\mathrm{NO_x}$ – ratio of emission with and without FGR on x)[18]

This solution, consequently, also destroys flue gas exergy, by lowering combustion temperature, and influences on thermal efficiency of boiler plant. Its impact on energy efficiency of boiler plant is very complex and isn't the topic of this research.

3.1. Influence of flue gases recirculation on exergy of flue gases

Exergy, also called available energy, is the maximum useful work that can be produced as the system is brought into equilibrium with its environment, by an ideal processes – reversible state changes [20]. As can be concluded, exergy of system is dependent on its state, but also on state of surroundings too (in energetic system primarily on temperatures and pressures). By implementing FGR system, exergy of flue gases is destructed because of lowering their temperature. Available energy of flue gases from isobaric atmospheric furnaces (approximately in boilers) is the work which can be produced by two (hypothetical and theoretical) reversible state changes: isentropic expansion to surroundings temperature, and, after that, isothermal compression to surroundings pressure. If adiabatic combustion is calculated, they are on T_{ad} and exergy can be determined by following expression (per unit of fuel) [21]:

$$e = c_p\left(T_{\mathrm{ad}} - T_o - T_o\, ln\frac{T_{\mathrm{ad}}}{T_o}\right) \tag{8}$$

where c_p is specific heat capacity of flue gases, and T_o is temperature of surroundings.

4. Analysis of the impact of flue gas recirculation on the emission of nitrogen oxides

All combustion modifications, including FGR, reduce primary the Zeldovich mechanism, with less success in prompt $\mathrm{NO_x}$ formation mechanisms. According to this fact, aim is to determine the impact of FGR on NO_x formation in one simplified case of adiabatic combustion of natural gas with composition and lower heating value given in Tab. 1. The moisture content in combustion air is neglected. The following simplifications were made: flame was treated as laminar, adopted fraction of thermal NO_x is equal 50%, equilibrium flue gas composition is just O_2, CO_2, H_2O and N_2. Impact of thermal dissociation on flame temperature and impact on prompt mechanisms was neglected. Coefficient of excess air λ depends on type of the fuel and on the point in the flue gas stream. Initial value of λ for gas fired furnaces is not great and it is equal approximately 1,02...1,08, and usually increases through the flue gases stream [19,23]. As the reactions of the formation of thermal NO_x do not take place in the burner, but after the process of flue combustion [7], the value of the coefficient of excess air was adopted 1,1 in the purpose of calculation in this paper.

The enthalpy dependances on temperature which were used are approximate second-order polynomial expressions $h_i = a_i T^2 + b_i T + c_i$ $[kJm^{-3}]$, where coefficients are different for each component [22]. According to theses approximations and energy balance, expression (7), combustion temperature is treated as function of recirculation coefficient x, $T_{\mathrm{ad}} = T_{\mathrm{ad}}(x)$. It is calculated as a solution of derived quadratic equation.Adopted extraction temperature is $T_{\mathrm{ex}} = 150°\mathrm{C} = 423\mathrm{K}$.

Table 1. Composition and lower heating value of considered natural gas

Component	CH_4	C_2H_6	C_3H_8	N_2	CO_2
Volume (mol) fraction[%]	90.3	5.8	0.2	3	0.7
Lower heating value LHV $[kJm^{-3}]$	36244				

When combustion is carried out using FGR, the oxidizer is a mixture of flue gases and air. In this way the availability of oxygen in flame is reduced. Oxygen fraction in oxidizer $O_{2\,\mathrm{ox}}$ after mixing with FGR, can be derived from mass balance of total flow and flow of oxygen through mixing box:

$$O_{2\,\mathrm{ox}} = \frac{0{,}21 V_L + \frac{x}{1-x} V_{O_2}}{V_L + \frac{x}{1-x} V_{rw}} \tag{8}$$

where V_L is the volume of air supplied for combustion per unit of the fuel.

The rate of thermal mechanism usually can be expressed by a well known modified Arrhenius form for chemical reaction rate [7,24]:

$$\frac{d[\mathrm{Q}]}{dt} = k(T) \cdot [\mathrm{M}]^m \cdot [\mathrm{N}]^n = A \cdot T^b \cdot exp\left(\frac{-E_{\mathrm{A}}}{R_u T}\right) \cdot [\mathrm{M}]^m \cdot [\mathrm{N}]^n \tag{9}$$

where $k(T)$ is global rate coefficient depanding on temperature T, A and b are empirical parameters, E_{A} is activation energy, R_u is universal gas constant, [Q], [M] and [N] are (molar) concentrations of product and reactants and *m* and *n* are exponents which relate to reaction order.

Following expression was used in this paper [8]:

$$\frac{d[\mathrm{NO}]}{dt} = 1.45 \cdot 10^{17} T^{-0{,}5} \cdot exp(\frac{-69460}{T}) \cdot [O_2]_{\mathrm{eq}}^{0.5} \cdot [N_2]_{\mathrm{eq}} \tag{10}$$

where $[O_2]_{\mathrm{eq}}$ and $[N_2]_{\mathrm{eq}}$ are equilibrium concentrations of oxygen and nitrogen in fuel gases, and T is temperature in [K]. Rate is expressed in $[mol\ cm^{-3} s^{-1}]$. Concentrations of each reactant is calculated as if they were ideal gases.

After these calculation impact on exergy of flue gases is calculated too. It's values are determined per mass unit, because it is usuall form of exergy presentation. Surroundings temperature T_{o} is 273K.

Specific heat capacity was calculated as linear function of temperature in form $c_{\mathrm{p}} = a_i T + b_i\ [kJ(kgK)^{-1}]$ by using data from [22].

5. Results of calculation and discussion

Influence of FGR on combustion temperature in considered case, and its percentage – relative decreasing δ_{T} and on relative decreasing of $\mathrm{NO_x}$ emitted by Zeldovich mechanism (δ_{z}) and relative emission, defined as fraction of amount of emitted $\mathrm{NO_x}$ with and without FGR system $\delta_{\mathrm{e}} = \frac{[NO_x]}{[NO_x|_{x=0}]}$ expreresed in percentages, is shown in Tab. 2 and graphical representation is given in Fig. 4a and 4b.

Table 2. Influence of FGR on combustion temperature and emission parameters

x	0	0.05	0.1	0.15	0.2	0.25	0.3
T_{ad} [K]	2214.07	2128.82	2043.16	1957.08	1870.57	1783.63	1696.26
δ_{T} [%]	0	3.85	7.72	11.61	15.51	19.44	23.39
δ_{Z} [%]	0	70.966	92.454	98.272	99.658	99.943	99.992
δ_{e} [%]	100	64.517	53.773	50.864	50.171	50.029	50.004

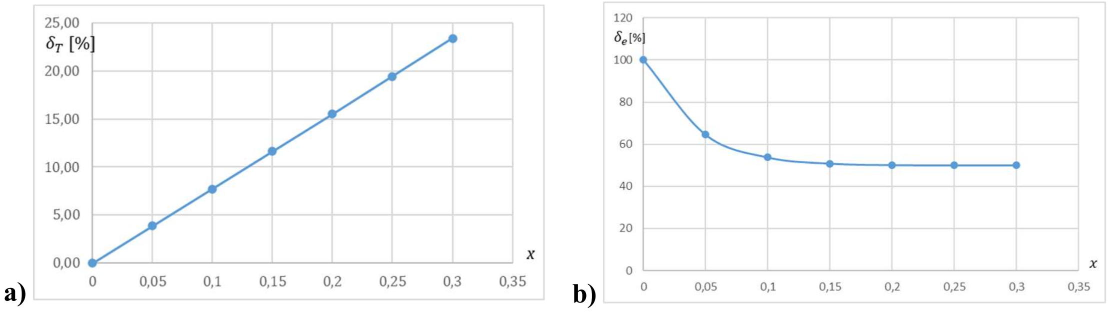

Figure 4. Influence of FGR on: a) temperature (relative temperature decreasing δ_{T}), and b) relative emission δ_{e}

Influence of FGR on oxidizer dilution, with important parameters for calculation is shown in Tab. 3.

Table 3. Influence of FGR on oxygen concentration in oxidizer and important parameters for calculation

x	0	0.05	0.1	0.15	0.2	0.25	0.3
$V_{\mathrm{L}}\ [m^3 m^{-3}]$	10.58	10.58	10.58	10.58	10.58	10.58	10.58
$\mathrm{O}_{2\ \mathrm{ox}}$[%]	21.0	19.95	18.91	17.87	16.85	15.84	14.84

The graphic representation is shown in the Fig. 5. Exergy and its relative decreasing δ_{ex} are presented in Tab. 4. and Fig. 6.

According to exposed results of calculation following facts are stand out. Temperature decreasing by FGR is incredibly significant, and at $x = 0.3$, reaches 23.39%. This causes lower Zeldovich $\mathrm{NO_x}$ emission. But very high values of x aren't justified, because of exponential dependance of Zeldovich mechanism on temperature, expression (10), and its rate's asymptotic tending to zero for higher temperature decreasing. Influence of FGR on combustion temperature and exergy is almost linear, and higher values of *x* contribute to destruction of exergy in flue gases and influence on energy efficiency of furnace and device without improvement of NO_x reduction, as can be seen in Tab. 2 and 4.

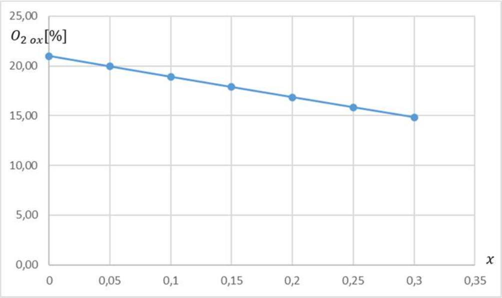

Figure 5. Graphic representation of dependance of oxygen fraction in oxidizer on FGR coefficient *x*

Table 4. Influence of FGR on exergy of flue gases

x	0	0.05	0.1	0.15	0.2	0.25	0.3
$e\ [kJkg^{-1}]$	2016.64	1889.398	1764.207	1641.134	1520.254	1401.648	1285.408
$\delta_{\mathrm{ex}}[\%]$	0	6.31	12.518	18.620	24.614	30.496	36.26

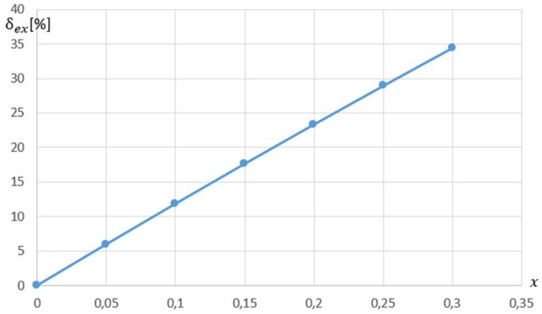

Figure 6. Graphic representation of dependance of exergy of flue gases on FGR coefficient *x*

For example, with an increase in the coefficient x, from 0.05 to 0.1, the temperature drops by an additional 3.87%, and the relative emission consequently decreases by 10.74%, while with an increase in *x* from 0.1 to 0.15, the temperature drops with almost the same intensity, while its contribution to emission reduction is lower, and δ_{e} is reduced by only 2.91%. Changing of exergy is proportional to *x*, as can be seen, so high intensities of recirculation impact on exergy decreasing for no practical improvements in emission reduction.

Relative emission (Fig. 4b) asymptotically tend to 50% (because assumption is that Zeldovich mechanism accounts 50% of total emission). Exceptionally good results are achieved by low values of *x*: by $x = 0.05$, $\delta_{\mathrm{e}} = 64.517\%$, and by $x = 0.1$, $\delta_{\mathrm{e}} = 53.773\%$, with acceptable impact on exergy, especially by low intensity of recirculation: for $x = 0.05$, $\delta_{\mathrm{ex}} = 6.31\%$.

Dilution of oxidizer is not great at low values of *x* (Fig. 5), and in those cases, according to Fig. 2, its contribution to NO_x emission reduction, for simple calculations can be neglected. Dependance (8) is almost linear, too. For example, by $x = 0.05 - 0.1$ concentration of oxygen is between 19.95% and 18.91%, so dilution is miserable. However, larger deviations were made for higher *x* (approximately for

$x > 0.15$ when $O_{2\ ox} < 17.87\%$), which usually aren't used in real plants. Then, neglecting of oxygen dilution for this study is rationally.

By increasing the values of x, upgrading in δ_e are negligible, and that operating conditions are pointless, because of high exergy decreasing, and other consequences that can occur (flame instability, etc.). By comparing results of calculation in this study, and diagram in the Fig. 3, it can be concluded that this calculation, with introduced assumptions, gives very good results, especially for low values of x, which are of interest for engineering practice.

5.1. Influence of extraction temperature on nitrogen oxides emission reduction and exergy of flue gases

Temperature of recirculated flue gases has impact on their exergy and on NO_x emission reduction. It's efects in case of adiabatic combustion of considered natural gas are presented in Fig. 7a and 7b. From these graphics can be concluded that T_{ex} has negligible impact on relative emission because of its exponential character, but greater impact is on exergy decreasing.

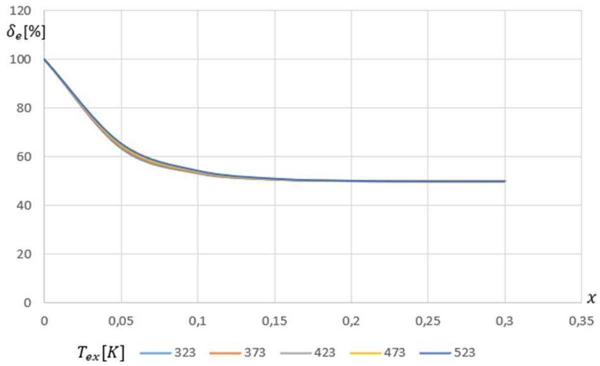

Figure 7. Influence of T_{ex} on relative emission of NO_x and relative exergy decreasing δ_{ex}

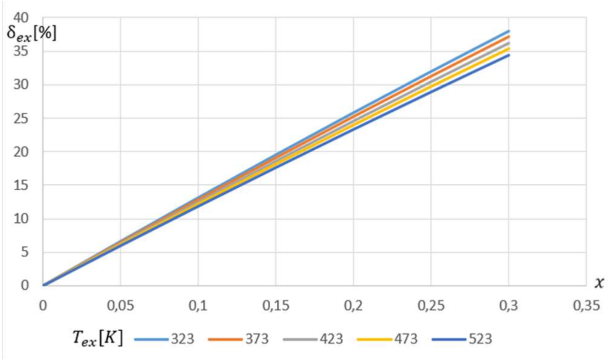

Figure 8. Influence of T_{ex} on relative exergy decreasing

So, lower temperature of extraction is pointless because of exergy destruction for no reason, even in range of usual FGR coefficients discussed above its impact on exergy is not high for all values of extraction temperature T_{ex}.

Data of calculation for some values of T_{ex} are given in Tables 5 and 6.

Table 5. Influence of T_{ex} on relative emission δ_{e} for diferent values of FGR coefficient

T_{ex}/x	0	0.05	0.1	0.15	0.2	0.25	0.3
373	100	64.031	53.502	50.764	50.143	50.022	50.003
423	100	64.517	53.773	50.864	50.171	50.029	50.004
473	100	65.021	54.064	50.976	50.205	50.037	50.006
523	100	65.542	54.378	51.103	50.245	50.047	50.008

Table 6. Influence of T_{ex} on relative exergy decreasing δ_{ex}

T_{ex}/x	0	0.05	0.1	0.15	0.2	0.25	0.3
373	0	6.475	12.842	19.099	25.241	31.264	37.162
423	0	6.310	12.518	18.620	24.615	30.496	36.260
473	0	6.144	12.191	18.140	23.985	29.724	35.352
523	0	5.978	11.864	17.656	23.352	28.947	34.439

6. Conclusion

Based on the presented results, it can be concluded that by low values of FGR coefficients (0.05…0.1), a very efficient and investment-cheap reduction of $\mathrm{NO_x}$ emissions can be achieved, with acceptable impact on the combustion temperature and thus on exergetic efficiency. By implementation of FGR systems in boilers, similar results are obtained as by using low $\mathrm{NO_x}$ burner, whose price is much higher than the price of installing the FGR system. The presented methodology is unique in that it provides a simplified way of calculating (reduced) nitrogen oxide emissions, as well as the analysis that accompanies it. The presented approach is suitable for use in practical analyses required when designing gas boiler systems. When using this methodology, it is important to keep in mind the deviations from exact values due to the assumptions made and the neglect of some influencing factors, especially at higher values of the coefficient x. Available studies are generally based on complex mathematical, mostly numerical, methods, which are often difficult for engineers in operational practice. In contrast, this paper shows how the issue at hand can be approached in a more straightforward manner while still obtaining results of satisfactory accuracy. Since natural gas is currently considered the cleanest fossil fuel and in some journal texts as energy source of the 21st century, significant attention in future research must be devoted to nitrogen oxide emissions, which represent its main drawback. Engineers in practice must have a simple and accessible mathematical apparatus for approximate calculations of impact of the FGR on the emissions of $\mathrm{NO_x}$. This study was small contribution to that purpose.

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Nomenclature

e – exergy of flue gases $[kJkg^{-1}]$
c_{p} – isobaric specific heat capacity of combustion products $[kJ(kgK)^{-1}]$
h_{cp}, h_i – enthalpy of combustion products and component i $[kJm^{-3}]$
T_{ad}, T_{ex}, T_{o} – temperatures of adiabatic combustion, flue gas extraction and surroundings [K]

V_{rec} – volume of recirculated combustion products $[m^3 m^{-3}]$
V_{rw}^{r}, V_{rw} – volume of total combustion products with and without FGR $[m^3 m^{-3}]$
V_i^r, V_i – volume of component *i* in combustion products with and without FGR $[m^3 m^{-3}]$
V_L – volume of combustion air $[m^3 m^{-3}]$
$\mathrm{O}_{2\ \mathrm{ox}}$ – oxygen concentration in oxidizer [%]
x – FGR coefficient [-]

Greek symbols
δ_{e} – relative emission of $\mathrm{NO_x}$ [%]
δ_{ex} – relative decreasing of exergy of flue gases [%]
δ_{T} – relative decreasing of combustion temperature [%]
δ_Z – relative decreasing of emission of Zeldovich mechanism's $\mathrm{NO_x}$ [%]
λ – excess air coefficient [-]

Acronyms
FGR – flue gas recirculation
LHV – lower heating value $[kJm^{-3}]$

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