

ANALYSIS OF NO_x FORMATION AT BURNING FUEL OIL AND NATURAL GAS FOR A 80 MW STEAM GENERATOR

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ABSTRACT

In this work has been developed a methodology to determine nitrogen oxides emissions (NO_x) in steam generators that burn both fuel oil and natural gas. The methodology is based on four main parameters related to combustion process in the furnace active burning zone (ABZ). Such parameters are the following ones: air excess coefficient in ABZ, average temperature in ABZ, reflected heat in ABZ and the residence time of combustion products in ABZ. As a tool to apply this methodology, there was a specially designed software which was named "NOX AD". It can calculate the four parameters above as well as the NO_x concentration for different operational methods to get a maximized reduction of NO_x.

The methodology was applied in a 350-ton/h (80MW) steam generator manufactured by Combustion Engineering, which is equipped with tangential burners and is currently working in the thermoelectric plant Ing. Jorge Luque located in the State of Mexico. The fuel oil used has a mass percentage composition of C=84.9%, S=3.8%, N=0.4%, H=10.8%, O=0.0% and W=0.0%. The natural gas has a volume percentage composition of CH₄ = 91.97%, C₂H₆ = 7.12% and C₃H₈ = 0.91%. Different methods of NO_x decrease were applied by using "NOX AD" software: gases recirculation, entrance place of recirculation gases, water injection in the ABZ, combustion at two stages and combinations of methods.

The determining of the four main parameters and the NO_x concentration that corresponded to each diminishing method were made under the following loads: 45%, 67%, 87% and 100%. The recirculation and water injection percentages were: 0%, 5%, 10% and 15%. The "NOX AD" software displays graphics that show the NO_x formation behavior for each

diminishing method. The results shows the maximized NO_x reduction when combinations of methods is applied.

INTRODUCTION

The formation process of nitrogen oxides at burning occurs due to oxidation of air nitrogen and nitrogen of fuel. Oxides of nitrogen (NO_x) which are formed in furnaces of steam generators represent the sum of nitrogen monoxide (NO), nitrogen dioxide (NO₂) and nitrogen gemoxide (N₂O). Quantity of NO₂ and N₂O does not exceed 2 % [1] and we shall consider therefore that NO_x = NO. Nowadays, three mechanisms are known on which there is formation of nitrogen oxides: thermal, fast and fuel. At formation of thermal and fast oxides a source of air nitrogen acts. In case of formation fuel NO_{fuel} a source is nitrogen of fuel.

The formation mechanism of thermal oxides of nitrogen has been explained by Zeldovich [2]. This explanation has been used in many other investigations. The reactions of thermal NO_{th} formation are characterized by high energy activation. Nitrogen oxides process occurs in a field with high temperatures exceeding 1800 K, Bartok [4].

Further, on length of a torch the oxides concentration practically does not vary according to Miller and Roslyakov [5 and 6]. Formation process of NO_x is determined with the following major factors: temperature in the active burning zone, density of reflected heat flow in ABZ, air excess coefficient and time of residence of combustion products in ABZ, from Roslyakov [3, 7].

The temperature in the active burning zone influences the NO_{th} formation process. Researches on kinetic model, developed by Roslyakov [6] have shown that temperature raise in active burning zone causes exponential NO_{th} concentration growth in combustion products.

The time to achieve an equilibrium concentration for nitrogen oxide in a range of temperatures 1800 to 1900 K is approximately 4 to 20 seconds. In boiler furnaces the residence time of combustion products is smaller, Kotler [1]. Hence, the equilibrium concentration is not reached.

Many authors have investigated the influence of air excess on nitrogen oxides formation, Roslyakov [7] shows that the dependence of $C_{NO_x} = f(\alpha)$ has extreme character with a maximum at burning natural gas and boiler oil in the field of values of air excess coefficient $\alpha_{cr} = 1.10$ to 1.25.

Fenimore [8] pointed out it's obvious that in front of a flame, in a short time interval appears nitrogen oxides formation. These nitrogen oxides are called "fast" because of the high speed formation on the basis of torch. Reactions of fast nitrogen oxides formation occur at temperatures from 1200 to 1600 K when thermal nitrogen oxides process practically does not occur. Dependence of fast NOx formation from air excess has a maximum at $\alpha = 0.6$ to 0.9, Roslyakov [7, 9] has showed, that there are two areas of air excess in which there is NO formation.

NOMENCLATURE

T'_{ad}	[K]	Adiabatic flame temperature for incomplete fuel combustion in ABZ
R	$[m^3 / m^3_{fuel}]$	Recirculation gases fraction
N	[-]	Dependent factor on input method of the recirculation gases
$\bar{\psi}_{ABZ}$	[-]	Absorptivity coefficient average of ABZ surfaces
c_{gas}	$[MJ/m^3]$	Thermal capacity average of combustion product
c_{air}	$[MJ/m^3]$	Thermal capacity average of air
c_m	$[MJ/m^3]$	Thermal capacity average of steam
Q_L	$[MJ/m^3]$	Low heat value of fuel
Q_{fuel}	$[MJ/m^3]$	Physical heat of fuel injected in ABZ
Q_{air}	$[MJ/m^3]$	Heat brought in ABZ with hot air
Q_{rec}	$[MJ/m^3]$	Heat brought in ABZ with gases of recirculation
Q_m	$[MJ/m^3]$	Heat brought in ABZ by injection of water
V^0_{gas}	$[m^3 / m^3_{fuel}]$	Theoretical volume of combustion products
V^0_{air}	$[m^3 / m^3_{fuel}]$	Theoretical volume of air for burning a unit of fuel
β	[-]	combustion efficiency
α_{burn}	[-]	Air excess coefficient in the burner
τ_{ABZ}	[s]	Residence time of gases in ABZ
q_{ABZ}^{refl}	$[MW/m^2]$	Reflected heat flux in ABZ
$C_{no_x}^m$	[ppm]	Nitrogen oxides concentration
G	$[m^3_{water} / m^3_{fuel}]$	Part of moisture brought in ABZ
A_i	$[m^2]$	Area of surfaces in ABZ
ψ_i	[-]	Absorptivity coefficient each surface
q_{ABZ}	$[MW/m^2]$	Absorbed heat flux in ABZ
A_{ABZ}	$[m^2]$	Total area of ABZ surfaces
A	[m]	Burner's width
B	[m]	Burner's depth
$C_{ABZ}^{R,g}$	[m]	Height of ABZ
B	$[m^3_{fuel} / s]$	Fuel rate
$V_{ABZ}^{R,g}$	$[m^3 / m^3_{fuel}]$	Volume of gases in ABZ
\bar{T}_{ABZ}	[K]	Average temperature of gases in ABZ
ξ	[-]	Filling factor of ABZ with combustion products
α_{gas}^{rec}	[-]	Air excess coefficient of recirculation gases
V_{ABZ}	$[m^3_{cp} / m^3_{fuel}]$	Volume of combustion products without recirculation gases and injected water into ABZ

METHOD OF NO_x CALCULATION

In boilers furnaces all kinds of nitrogen oxides are formed, it is in a zone where the basic quantity of fuel burns down and gases temperature is higher than 1800 K [2, 4]. This zone is designated as an active burning zone [7, 9, 10]. In works [7, 9] it can be appreciated, that nitrogen oxides formation in active burning zone (ABZ) completely depends on four basic thermo-physical parameters. Those parameters are: air excess coefficient (α_{ABZ}), average temperature in ABZ (\bar{T}_{ABZ}), density of reflected heat flux in ABZ (q_{ABZ}^{refl}) and time of residence of gases in ABZ (τ_{ABZ}). The quantity of nitrogen in fuel is important too. One of the major characteristics is the average temperature of combustion products in active burning zone. This temperature is determined by [11]:

$$\bar{T}_{ZCA} = T'_{ad} (1 - \bar{\psi}_{ZCA})^{0.25} (1 - r^{1+nr}) \quad (1)$$

The adiabatic temperature of burning for incomplete fuel combustion is determined under the equation:

$$T'_{ad} = \frac{\beta_{comb} PCI + Q_{aire} + Q_{rec} + Q_{comb} + Q_{agua}}{\beta_{comb} V^0_{gas} C_{gas} + 1.0161(\alpha_{quem} - \beta_{comb}) V^0_{aire} C_{aire} + 1.24 g C_{agua}} + 273 \quad (2)$$

c_{gas} , c_{air} and c_m can be determined under recommendations [11].

The absorptivity coefficient average for active burning zone is determined by the equation:

$$\bar{\psi}_{ZCA} = \frac{\sum \psi_i A_i}{\sum A_i} \quad (3)$$

It is known, that the temperature provides the most essential influence on nitrogen oxides generation. According to definition the integral temperature average in ABZ is:

$$\bar{T}_{ABZ} = \int_0^{\tau_{ABZ}} T d\tau / \tau_{ABZ} \quad (4)$$

Roslyakov [9] shows that the level of maximum values for concentration of nitrogen oxides does not depend on integrated temperature average, but on the highest gases temperature in ABZ. However, it is not possible to calculate the highest temperature in ABZ. Therefore, in [7] another ABZ characteristic is offered. It is the reflected heat flux in the active burning zone which is determined under the equation:

$$q_{ZCA}^{refl} = q_{ZCA} (1 - \bar{\psi}_{ZCA}) \quad (5)$$

Where the absorbed heat flux in ABZ (q_{ABZ}) can be calculated under:

$$q_{ZCA} = \frac{B(\beta_{comb} PCI + Q_{comb} + Q_{aire} + Q_{rec} + Q_{agua})}{A_{ZCA}} \quad (6)$$

Another important parameter is the air excess coefficient, which is determined by air excess coefficient in burners and air which has been brought with recirculation gases:

$$\alpha_{ZCA} = \alpha_{quem} + r(\alpha_{rec} - 1) \quad (7)$$

The investigations carried out in [9, 10] have shown, that dependence of fast NO formation from air excess coefficient at constant temperature has extreme character and thermal nitrogen oxides formation with air excess has an exponential character [3].

The sum of all kinds of nitrogen oxides (fast, fuel and thermal) will characterize generally final concentration of nitrogen oxides. In work [9] it was offered to use a polynomial of fourth degree for description of influence of air excess coefficient on final concentration of nitrogen oxides on outlet from active burning zone.

The residence time of combustion products in ABZ is determined by Roslyakov et al. [9 and 10]:

$$\tau_{ABZ} = \frac{a \cdot b \cdot c_{ABZ}^{R,g} \cdot \xi}{B \cdot V_{gas}^{R,g} \cdot (\bar{T}_{ABZ} / 273)} \quad (8)$$

ξ was determined in [11] as 0.7 for furnaces with direct-flow using tangential burners located in corners of furnace.

The volume of combustion products in ABZ including the recirculation gases and the injected water is calculated under the equation:

$$v_{ZCA,rec,g} = \beta_{comb} v_{gh}^0 + 1.0161(\alpha_{quem} - \beta_{comb})v_{aire}^0 + 1.24g + r[v_{gh}^0 + 1.061(\alpha_{rec} - 1)v_{aire}^0 + 1.24g] \quad (9)$$

The height of ABZ depends on the geometrical sizes of the active burning zone and the relation of combustion products volumes in ABZ:

$$c_{ABZ}^{R,g} = c_{ABZ} \frac{V_{ABZ}^{R,g}}{V_{ABZ}} \quad (10)$$

The volume of combustion products without recirculation gases and injected water into ABZ (V_{ABZ}):

$$v_{ZCA} = \beta_{comb} v_{gh}^0 + 1.0161(\alpha_{quem} - \beta_{comb})v_{aire}^0 \quad (11)$$

The equation for the calculation of nitrogen oxides concentration (in ppm) in combustion products is offered by Roslyakov [7]:

Burning Natural gas:

$$C_{NO_x} = \left[26.0 \exp\left(0.26 \frac{\bar{T}_{ZCA} - 1700}{100}\right) - 4.7 \right] \left[\exp(q_{ZCA}^{ref}) - 1 \right] \cdot [13.0 + 9.6(\alpha_{ZCA} - 1.07) + 59.4(\alpha_{ZCA} - 1.07)^2 + 18.1(\alpha_{ZCA} - 1.07)^3 + 79.8(\alpha_{ZCA} - 1.07)^4] \cdot \tau_{ZCA}$$

Burning fuel oil:

$$C_{NO_x} = \left[24.3 \exp\left(0.19 \frac{\bar{T}_{ZCA} - 1650}{100} - 12.3 \right) \right] \left[\exp(q_{ZCA}^{ref}) - 1 \right] \cdot [15.1 + 2.8(\alpha_{ZCA} - 1.09) + 73.0(\alpha_{ZCA} - 1.09)^2 + 72.3(\alpha_{ZCA} - 1.09)^3 + 131.7(\alpha_{ZCA} - 1.09)^4] \cdot \tau_{ZCA}$$

TRENDS AND RESULTS

GASES RECIRCULATION

The first issue to be analyzed is the effect presented in the NOx concentration when the recirculation gases changes in the steam generator. Table 1 shows the four main parameters (fuel oil and natural gas) on which NOx concentration depends, as

well as the concentration for different loads and percentages recirculation gases itself.

Table 1. NOx formation with recirculation gases.

NATURAL GAS						
recirculation fraction	%	\bar{T}_{ZCA} , K	q_{ZCA}^{ref} , MW/m ²	τ_{ZCA} , s	α_{ZCA}	C_{NO_x} , ppm
0	100	1881.54	0.361	0.58	1.100	125.33
	84	1881.54	0.303	0.69	1.100	121.54
	67	1881.54	0.241	0.87	1.100	117.71
	45	1881.54	0.162	1.29	1.100	112.97
0.05	100	1744.69	0.348	0.63	1.108	86.53
	84	1744.69	0.292	0.75	1.108	83.95
	67	1744.69	0.233	0.94	1.108	81.39
	45	1744.69	0.156	1.40	1.108	78.24
0.10	100	1643.76	0.336	0.67	1.116	64.39
	84	1643.76	0.282	0.79	1.116	62.58
	67	1643.76	0.225	0.99	1.116	60.75
	45	1643.76	0.151	1.48	1.116	58.47
0.15	100	1559.02	0.325	0.70	1.124	49.40
	84	1559.02	0.273	0.84	1.124	48.06
	67	1559.02	0.217	1.05	1.124	46.69
	45	1559.02	0.146	1.56	1.124	45.00
FUEL OIL						
0	100	2012.96	0.414	0.48	1.10	135.89
	84	2012.96	0.348	0.57	1.10	131.18
	67	2012.96	0.277	0.72	1.10	126.41
	45	2012.96	0.186	1.07	1.10	120.54
0.05	100	1866.04	0.400	0.52	1.108	94.93
	84	1866.04	0.336	0.62	1.108	91.75
	67	1866.04	0.268	0.78	1.108	88.54
	45	1866.04	0.179	1.16	1.108	84.56
0.10	100	1757.61	0.387	0.55	1.116	69.92
	84	1757.61	0.325	0.66	1.116	67.66
	67	1757.61	0.259	0.82	1.116	65.36
	45	1757.61	0.173	1.23	1.116	62.52
0.15	100	1666.55	0.375	0.58	1.124	51.98
	84	1666.55	0.315	0.69	1.124	50.35
	67	1666.55	0.251	0.87	1.124	48.70
	45	1666.55	0.168	1.30	1.124	46.65

It is possible to observe that if gases recirculation amount increases then NOx concentration lowers, since the gases which have low temperature are distributed in the furnace and show a reduction effect in temperature.

Regarding the reflected heat, it is possible to observe its reduction as soon as the recirculation gases amount increases. This happens because when low temperature gases enters in furnace, the heat transfer phenomenon is affected. It also happens that, when there is a small load, the reflected heat diminishes because a lower amount of fuel is burnt. Therefore, there is a lower energy amount in transmission.

The residence time is inversely proportional to fuel consumption. That is why, when the load increases the residence time is low. On the other hand, for the same load and with an increased recirculation gases percentage, there is a raise in the residence time which is mainly due to a reduction in the furnace average temperature.

Regarding the NOx concentration, it is possible to see that when there is a small load the NOx concentration reduces due to the little fuel amount that is burnt. (See figures 1 and 2). It is

also possible to see that when the recirculation gases percentage is raised, the NOx concentrations go down mainly because the furnace average temperature drops, the residence time also affects it adversely.

This is, when the gases recirculation percentage is higher, the residence time is higher too. However, this increase affects less, if it is compared to the effect that the average temperature has on the NOx concentration.

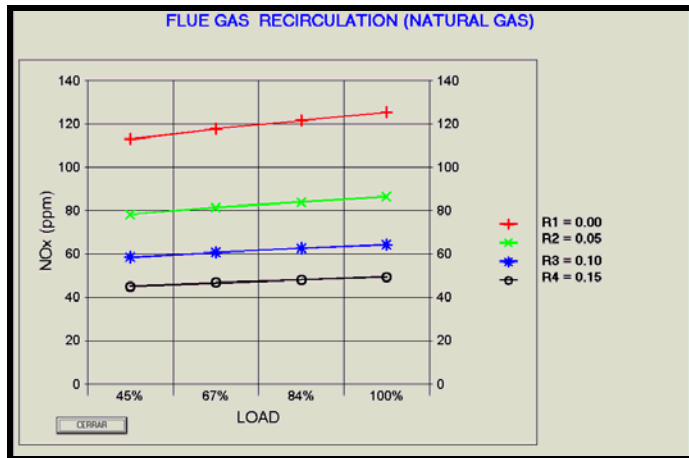


Figure 1. NOx formation depending on load in different percentages for natural gas recirculation

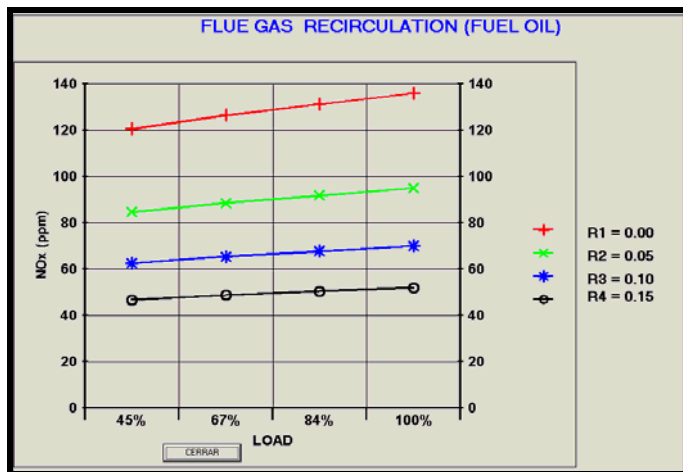


Figure 2. NOx formation depending on load in different recirculation percentage for fuel oil

In figures 1 and 2 it is possible to observe that the NOx concentrations are higher when there is no diminishing method applied. When the first 5% recirculation gases are supplied, the highest concentration reduction is obtained. On the other hand, when increasing the quantities of recirculation gases by 5% each time, the decrease in NOx formation goes down too. In the case of fuel oil, there is a similar behavior to the one of natural gas (See table 1 and figure 2).

The only difference is that because of the higher heat value of fuel and its sensitive heat, a great amount of variables is

modified. This impact is reflected in the four main parameters. This effect causes an increase in the main parameters values under the same operating conditions, except on the residence time, which is inversely proportional to the furnace average temperature. The greatest reduction of NOx when the gases recirculation is applied is 60.5% for natural gas and 61.7% for fuel oil.

DIFFERENT INTRODUCTORY PLACES OF GASES RECIRCULATION

The case in which we have different injection places of recirculation gases consists on observing the NOx concentration when the recirculation gases are introduced in the fuel duct (n=2), in the hot air duct (n=3), or in separate channels (n=5). The obtained results are shown in table 2.

Table 2 Results of NOx concentration when changing introduction place of escape gases.

CASE	\bar{T}_{ZCA} , K	q_{ZCA}^{ref} , MW/m ²	τ_{ZCA} , s	α_{ZCA}	C_{NOx} , ppm
NATURAL GAS					
n = 2	1621.30	0.336	0.67	1.116	60.60
n = 3	1643.76	0.336	0.66	1.116	64.39
n = 5	1675.77	0.336	0.65	1.116	70.09
FUEL OIL					
n = 2	-	-	-	-	-
n = 3	1757.61	0.387	0.55	1.116	69.92
n = 5	1791.83	0.387	0.54	1.116	76.43

According to the results for the natural gas, it is observed that there is a higher NOx concentration for (n=5) because there is nor a pre-mixture fuel-air, which affects the NOx concentration. In the case of (n=2) a lower NOx concentration is obtained because of the reduction on the furnace average temperature. In the case (n=3) a reduction of the furnace average temperature is also obtained. Nevertheless, it is not the same as the one gotten for that case in which (n=2).

The advantage obtained in the NOx concentration reduction when changing the gases injection place is 13% for natural gas and 8.52% for fuel oil.

METHODS COMBINATION: RECIRCULATION GASES, WATER INJECTION AND LOW AIR EXCESS

In the table 3 and figures 3 and 4 it is possible to see the results that correspond to the combination: recirculation gases, water injection and low air excess. The reason for making this combination is that, when lowering the air excess, carbon monoxide is build up in the products. To avoid this, it is necessary to inject water to the combustion chamber to form active reaction centers. The difference in the NOx concentration for the same load (100%) with and without application of reduction methods is 68.43ppm. According to table 3 this means a NOx reduction of 54.6 % for natural gas and of 58.63% for fuel oil.

Table 3. NOx formation with and without combination of reduction methods.

CASE	LOAD %	\bar{T}_{ZCA} , K	q_{ZCA}^{refl} , MW/m ²	τ_{ZCA} , s	α_{ZCA}	C_{NOX} , ppm
NATURAL GAS						
$r = 0$ $g = 0$ $\alpha_{quem} = 1.10$	100	1881.54	0.361	0.58	1.100	125.33
	84	1881.54	0.303	0.69	1.100	121.54
	67	1881.54	0.241	0.87	1.100	117.71
	45	1881.54	0.162	1.29	1.100	112.97
$r = 0.10$ $g = 0.15$ $\alpha_{quem} = 1.08$	100	1609.54	0.333	0.68	1.096	56.90
	84	1609.54	0.279	0.81	1.096	55.32
	67	1609.54	0.223	1.02	1.096	53.71
	45	1609.54	0.149	1.52	1.096	51.72
FUEL OIL						
$r = 0$ $g = 0$ $\alpha_{quem} = 1.10$	100	2012.96	0.414	0.48	1.100	135.89
	84	2012.96	0.348	0.57	1.100	131.18
	67	2012.96	0.277	0.72	1.100	126.41
	45	2012.96	0.186	1.07	1.100	120.54
$r = 0.10$ $g = 0.15$ $\alpha_{quem} = 1.08$	100	1697.11	0.373	0.57	1.096	56.21
	84	1697.11	0.313	0.68	1.096	54.46
	67	1697.11	0.249	0.85	1.096	52.69
	45	1697.11	0.167	1.28	1.096	50.48

NOx REDUCTION METHODS COMBINATION

In table 4 and in figures 5 and 6 it is possible to see the results in which the steam generator works under the plant's normal conditions, that is load 100% and 10% of recirculation gases and without water injection. In the second case it is considered that it works with 10% recirculation, 15% water injection and low air excess and lastly when it works with 10% gases recirculation and combustion at two stages without water injection. For two combustion stages in the steam generator furnace it is intended to introduce 100% of fuel in the burner's two inferior levels and in all the three levels to introduce 33.33% of the required air per unit of fuel. This causes the formation of two zones of combustion: one rich in fuel and another in air.

Table 4. Results of NOx reduction methods combination.

CASE	LOAD	\bar{T}_{ZCA} , K	q_{ZCA}^{refl} , MW/m ²	τ_{ZCA} , s	α_{ZCA}	C_{NOX} , ppm
NATURAL GAS						
$r = 0.10$ $g = 0$ $\alpha_{quem} = 1.10$	100	1643.76	0.336	0.67	1.116	64.39
	84	1643.76	0.282	0.79	1.116	62.58
	67	1643.76	0.225	0.99	1.116	60.75
	45	1643.76	0.151	1.48	1.116	58.47
$r = 0.10$ $g = 0.15$ $\alpha_{quem} = 1.08$	100	1609.54	0.333	0.68	1.096	56.90
	84	1609.54	0.279	0.81	1.096	55.32
	67	1609.54	0.223	1.02	1.096	53.71
	45	1609.54	0.149	1.52	1.096	51.72
$r = 0.10$ $g = 0$ $\alpha_{quem} = 0.733$	100	1460.08	0.251	0.90	0.749	34.68
	84	1460.08	0.211	1.07	0.749	33.96
	67	1460.08	0.168	1.34	0.749	33.22
	45	1460.08	0.113	2.00	0.749	32.29
FUEL OIL						
$r = 0.10$ $g = 0$ $\alpha_{quem} = 1.10$	100	1757.61	0.387	0.55	1.116	69.92
	84	1757.61	0.325	0.66	1.116	67.66
	67	1757.61	0.259	0.82	1.116	65.36
	45	1757.61	0.173	1.23	1.116	62.52
$r = 0.10$ $g = 0.15$ $\alpha_{quem} = 1.08$	100	1697.11	0.373	0.57	1.096	56.21
	84	1697.11	0.313	0.68	1.096	54.46
	67	1697.11	0.249	0.85	1.096	52.69
	45	1697.11	0.167	1.28	1.096	50.48
$r = 0.10$ $g = 0$ $\alpha_{quem} = 0.733$	100	1534.18	0.250	0.91	0.750	32.77
	84	1534.18	0.210	1.08	0.750	32.11
	67	1534.18	0.160	1.36	0.750	31.43
	45	1534.18	0.110	2.02	0.750	30.57

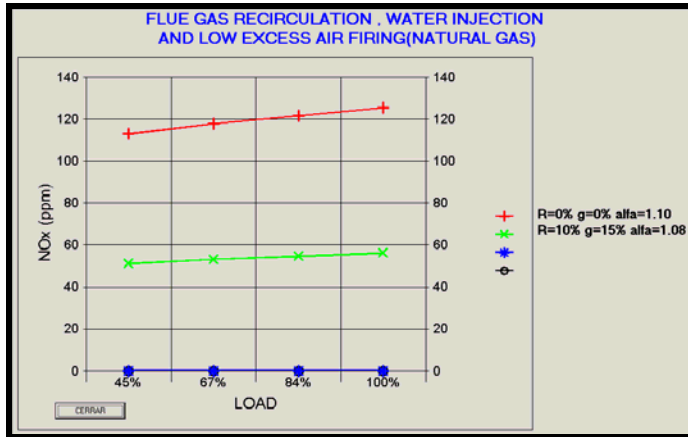


Figure 3. NOx formation without reduction methods and with the combination: gases recirculation, water injection and low excess of air for natural gas.

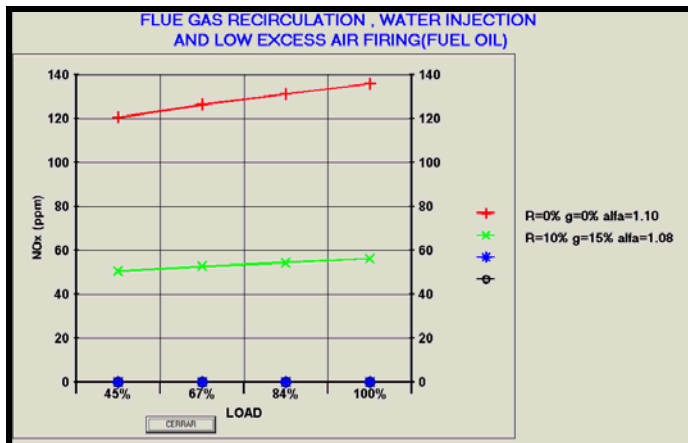


Figure 4. NOx formation without reduction methods and with the combination; gases recirculation, water injection and low air excess for fuel oil.

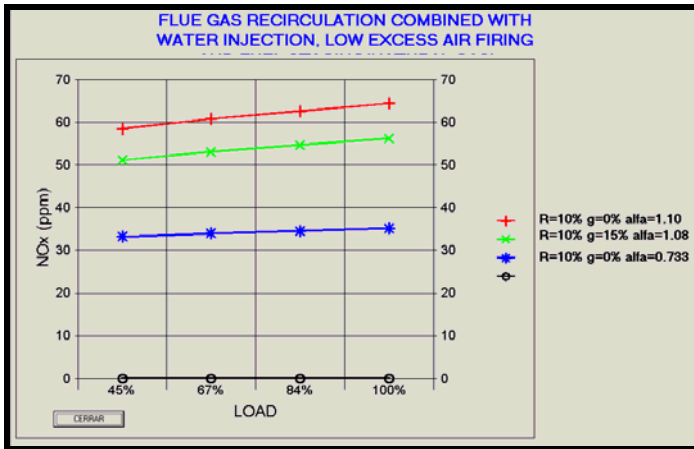


Figure 5. NOx reduction methods combination: Conventional, with water injection and with two combustion stages for natural gas

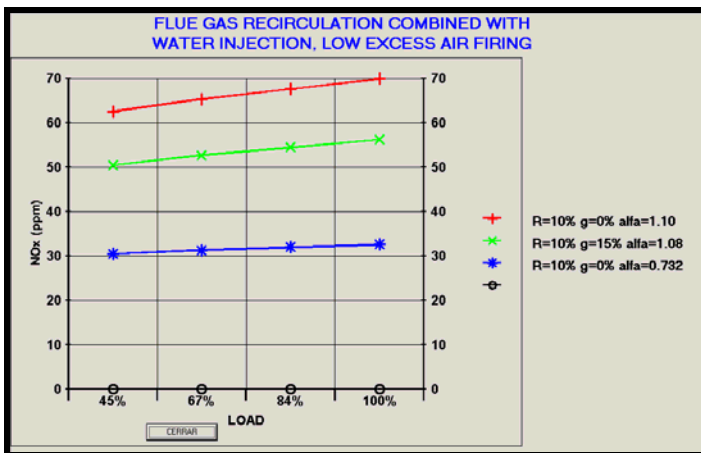


Figure 6. NOx reduction methods combination: Conventional, with water injection and low air excess and with two combustion stages for fuel oil.

In table 4 it is seen that the variation in the reduction of NOx concentration is 11.63% for natural gas when the steam generator works with 10% recirculation, 15% of water and low air excess.

The reduction that is obtained in the NOx concentration with this last condition leads to the conclusion that the effect of the combustion at two stages in the NOx concentration is far more significant than the effect of water injection. If we compare the NOx reduction that is gotten when applying the proposed reduction methods it is possible to see that for the case in which the steam generator works with 10% recirculation of escape gases, we get a reduction of 48.62% of NOx concentration. For the case in which the steam generator additionally works with 15% of water injection and low air excess we get a reduction of 54.6% in NOx concentration. And finally, when we have a 10% of gases recirculation with two combustion stages, there is a NOx reduction of 74.23%. These results show the advantage of using de gases recirculation combination with two combustion stages regarding all the other analyzed methods.

CONCLUSION

For the application case, the NOx concentration calculation was carried with the proposed methodology in a steam generator of 350 ton/h (80 MW). Using the software "NOx AD" for the application example, the resulting NOx concentration without the reduction methods application for natural gas and fuel oil working at a load of 100% are 125 ppm and 135 ppm respectively. These results show that the NOx formation is greater when burning fuel oil compared to natural gas. This agrees completely with the literature revision.

On the other hand, the NOx concentration when changing the location of the recirculation gases introduction is 13% for natural gas and 8.52% for fuel oil, both being small values. However, this method represents an alternative to be considered. The maximum NOx reduction is 14% when applying the water injection compared to the 61% NOx reduction which results from the gases recirculation method with the same operation conditions.

The maximum reduction is obtained when the steam generator works with two combustion stages and 10% gases recirculation and it is 72.33%. That is why it is observed that the main effect in the NOx reduction is due to the gases recirculation. Comparing the results of the software "NOx AD" and the average values measured in the thermoelectric plant (without applying the NOx reduction methods); we get a maximum difference of 5%.

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