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Nox Emissions Dependencies on Gas Recycling in A 132 mw Steam Boiler

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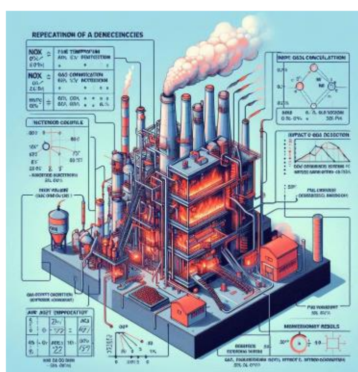
Abstract

This paper presents the calculation of the concentration of nitrogen oxides (NOx) in the furnace of a 132 MW steam generator located at the CELEC EP THERMOELECTRIC PLANT TERMOESMERALDAS BUSINESS UNIT in the Republic of Ecuador. This steam generator is equipped with two levels of tangential burners located at each corner of the furnace, which burn type 6 fuel oil tangentially in a vertical whirlwind. A verification thermal calculation method has been developed for the furnaces of the steam generators, from which the concentration of NOx has been determined at different operating load levels (100%, 75% and 50%) with different percentages of gas recirculation (0%, 10% and 20%), maintaining a fixed coefficient of excess air of 5%. This calculation was performed using Excel, which allowed the identification of operating conditions that could reduce NOx formation while maintaining adequate thermal efficiency.

Keywords: *Fuel Oil Combustion, Two Stages, Nitrogen Oxides, Thermal Calculation, Steam Generator.*

Introduction

Graphical Abstract



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In recent years, there has been a growing recognition of the need to reduce emissions of harmful substances into the atmosphere from thermal power plants. At least, there has been a need to reduce these emissions to the level regulated by the standards of each country. This recognition has led to the use of both construction and technological methods to suppress the formation of nitrogen oxides. A substantial proportion of the technological methods for NOx suppression have undergone rigorous testing in industrial settings and have been documented in both domestic and foreign technical publications.

The environmental sustainability of energy installations necessitates the maintenance of regulated limits on the potential adverse impacts of these installations on the natural environment. The regulation of negative consequences is due to the fact that it is impossible to completely eliminate environmental damage. In the context of fossil fuel thermoelectric power plants, the combustion process gives rise to emissions of various pollutants, including carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), gaseous inorganic chlorine compounds, and fluoride. To mitigate the potential health and environmental impacts of these emissions, a range of preventive measures and actions can be implemented during the combustion process, with the objective of maintaining these emissions at levels below certain critical limits (9).

With regard to NOx emissions, they are predominantly generated by the oxidation of nitrogen from combustion air at elevated temperatures (thermal NOx) and by the oxidation of nitrogen from fuel (fuel NOx), which can occur at lower temperatures. The formation of thermal NOx is contingent on the local temperature of the flame, while the formation of fuel NOx is predominantly influenced by the nitrogen content of the fuel and the oxygen available in the flame within the particulate combustion zone.

Several parents have attested to their children's utilization of songs for educational purposes at home, including counting, addition, subtraction, and more general recreational learning activities. However, a significant number of parents do not utilize songs that are specifically designed to instruct children in mathematics, suggesting that the role of music in the home is predominantly oriented towards entertainment rather than reinforcing mathematical concepts.

As posited by several parents, the learning of songs with mathematical themes, such as counting or addition, has been demonstrated to facilitate enhanced retention of numerical values and sequence. This lends further credence to the notion that musical compositions can serve as an effective medium for reinforcing mathematical concepts in a natural and engaging manner. Furthermore, some parents have noted that their children derive pleasure from engaging in singing and movement concurrently with learning, thereby reinforcing the notion that the integration of music, movement, and learning is a potent catalyst for the development of mathematical aptitude.

Figure 1 provides a comprehensive summary of the major contributors to NOx produced during combustion.

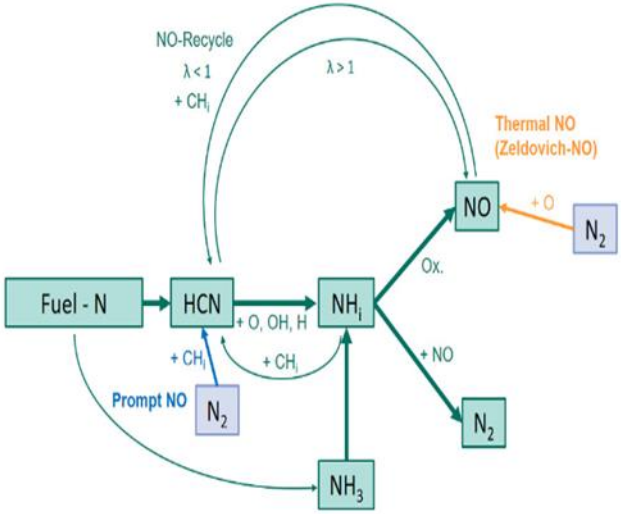

Figure 1. NOx Formation Mechanism (14).

The main source of NO in high-temperature gas combustion is the thermal NO or Zeldovich mechanism (Eq. 1) /11/

$$O + N_2 \rightarrow NO + N \quad (1)$$

$$N + O_2 \rightarrow NO + O \quad (2)$$

$$N + OH \rightarrow NO + H \quad (3)$$

Nitrogen dioxide (NO2) poses a significant environmental threat due to its ability to rapidly oxidize in water vapor within clouds, resulting in the formation of nitric acid (HNO3), a primary component of acid rain. When these acids are present in raindrops, they exhibit high reactivity with organic and inorganic substances, potentially causing damage or destruction to soil, water, plants, animals, and buildings (13).

Acid rain precipitation has been demonstrated to remove essential nutrients from the soil and release aluminum, thereby hindering the absorption of water by trees. Furthermore, they have been observed to cause damage to conifer needles and tree leaves. The harmful effects of NOx on human health are primarily focused on the respiratory system. In the Republic of Ecuador, the emission of NOx is subject to regulation at levels below 400 milligrams per cubic meter (15). As part of the air protection measures implemented in urban areas where these thermal power plants are located, there is an imperative to reduce emissions of oxides of (NOx). The analysis of these measurements indicates the necessity of reducing the temperature within the flame's core and the amount of oxidizing agent, that is, oxygen. The most significant of these measures are: recirculation of combustion products, application of the burner with low NOx concentration, the introduction of air and fuel in several stages, and the combination of these measures.

Consequently, the reduction of nitrogen oxides can be achieved through technological measures (regime, primary) that do not necessitate substantial capital investments. Modern oil-fired boilers are typically equipped with gas recirculation devices, which are the most prevalent technological measure. When implemented effectively, these devices can reduce nitrogen oxide concentrations to the levels stipulated by the country's environmental legislation.

The impact of gas recirculation has been thoroughly examined in the context of biomass and coal co-combustion boilers (10). The findings of this study indicated that under the thermodynamically assessed conditions, the recycling of 10% of the flue gases resulted in a negligible formation of NOx. According to the findings of other studies (11), the implementation of gas recirculation during the process of natural gas combustion has been demonstrated to result in a reduction of NOx emissions ranging from 15 to 20%. In the context of liquid fuel boilers (12), significant NOx reductions of up to 40% were attained.

An investigation was conducted into the impact of gas recirculation on NOx emissions in a full-scale 130 tonnes/hour medium-pressure (20 kg/cm²) steam boiler utilizing an oil-gas mixture, with the objective of identifying the optimized energy cost operating model (13). The authors posit that the implementation of gas recirculation has the potential to reduce NOx emissions, concurrently leading to a reduction in fuel costs and an enhancement in the efficiency and economic viability of the boiler operation.

The extant studies concur that the recirculation of gases engenders a decrease in NOx emissions. However, the reported values of this decrease vary considerably and are contingent on the percentage of recycled gases, the operating parameters of the boilers, and the type of fuel utilized.

In this work, a methodology is developed to evaluate NOx emissions at different loads in a steam generator operating in the 132 MW Thermoelectric Plant of the Company CELEC EP TERMOESMERALDAS BUSINESS UNIT of the Republic of Ecuador. The methodology enables the evaluation of the influence of the percentage of gas recirculation on NOx emissions and boiler efficiency. A comparison of the results obtained with experimental measurements was conducted, thereby demonstrating the methodology's capacity to predict NOx emissions from the design stage.

Materials and Methods

Description of the Installation

This type 6 oil burning steam generator, water tube, from the firm FRANCO TOSÍ under the Combustion Engineering License, with the characteristics in Table 1.

Caldera FRANCO TOSI	**Units**	**50 %**	**75 %**	**100 %**
Superheated steam generation	kg/h	216000	324000	432000
Superheated Vapor Pressure	kg/cm2	144	144	144
Pressure in the dome	kg/cm2	146,5	149,3	153,1
Superheated steam temperature	°C	540	540	540
Feed Water Temperature	°C	205	226,5	245
Reheated Steam Flow	kg/h	191500	287000	383000
Reheated Vapor Pressure	kg/cm2	18,1	27,3	35,1
Reheated steam temperature	°C	540	540	540
Fuel Type	Fuel Oil No.6			
Average fuel temperature	°C	72,5		
Forced draft fan	Kw	1500		
Gas Recirculation Fan	Kw	438		

Table 1. Characteristics Of Type 6 Oil Burning Steam Generator, Water Tube, From the Firm FRANCO TOSÍ.

Fuel oil No. 6 has the following elemental chemical composition shown in Table 2

Hydrogen(H)	10,43
Nitrogen (N)	0,30
Oxygen (O)	0,36
Sulphur (S)	2,07
Ashes (A)	0,07
Humidity(W)	0,79

Table 2. Elemental Chemical Composition of Fuel Oil 6

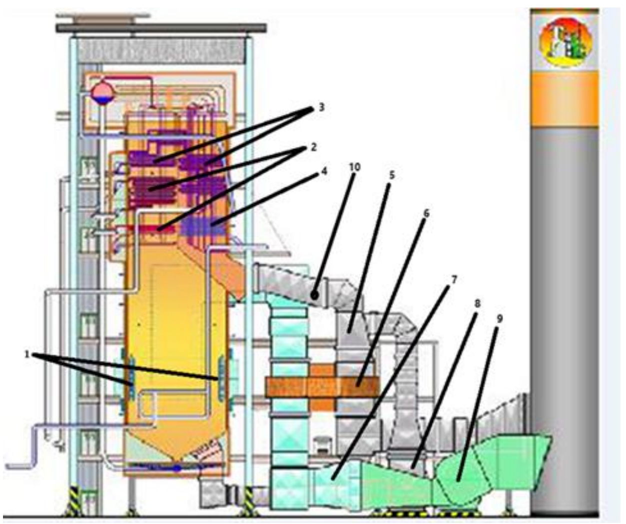

Figure 2. Schematic diagram of the Franco Tosi boiler. Termo 1 business unit. CELEC EP. Emeralds

1.-Burners; 2.- Steam superheaters; 3.- Steam reheaters; 4.-Economizer; 5.- Flue of gases resulting from combustion; 6.-Regenerative air heater; 7.- Air duct; 8.- Gas recirculation fan; 9.- Forced draft fan; 10.- Point of measurement of the characteristics of the gases produced by combustion.

The boiler draft system is of the forced type, it uses a fan to supply combustion air. This air is preheated with a steam coil, and then further heated in a regenerative air heater (CAR), Figure 2, with a 60 m high chimney, with an outer diameter of approximately 5.6 m at the top and an effective diameter of 3.4.

The fuel feed is with bayonet type burners, Y-mixture steam-fuel with pellet and atomizer with an angle of 80 degrees, on two levels, located in the corners of the furnace as shown in Figure 3.

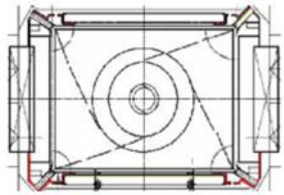

Figure 3. Burner Layout

The 132 MW steam generator furnace has the dimensions shown in Figure 4 a and b.

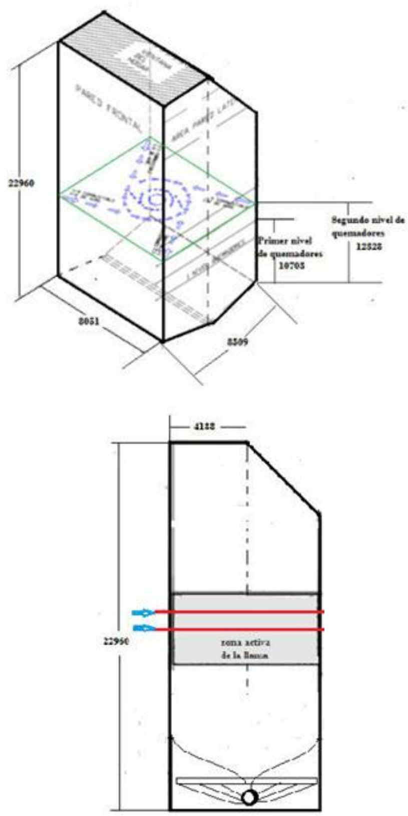

Figure 4. Steam Generator Furnace Dimensions

Oven; b) Active combustion zone

At present, it is not possible to know exactly the level of NOx contamination because, because the measuring equipment is not in good condition and also in some operating conditions gases are not recirculated because when recirculating the temperature of the reheating vapor is increased due to anomalies in the desuperheater, then it was necessary by analytical means to obtain what are the appropriate operating conditions for different loads and several % of recirculation of the gases.

Calculation Methodology

The calculations were developed in Excel from the elemental chemical composition of fuel oil

No. 6, making a sequence of calculations, from the elemental chemical composition of the fuel oil No. 6 used and the operation data of this steam generator and its construction characteristics in the following order:

Calculation of the volume of air required for combustion and the volumes of gases as a result of stoichiometric combustion.

Calculation of the enthalpy of the air of the gases produced by combustion.

1. Calculation of thermal efficiency of the steam generator by the input and output method (Direct).

2. Calculation of the temperature of the gases at the furnace outlet

3. Calculation of NOx concentration.

This allows to use the results of each calculation in the next one and finally obtain the concentration of NOx.

1. Equations used in the calculation of the volume of air required for combustion and the volumes of gases as a result of stoichiometric combustion (5).

$$V^o = 0{,}0889\left(C^t + 0{,}375S^t_{p+o}\right) + 0{,}265H^t - 0{,}0333O^t, m^3/kg$$

$$V^o_{RO_2} = 1{,}866\frac{(C^t + 0{,}375S^t_{p+o})}{100}, m^3/kg$$

$$V^o_{N_2} = 0{,}79V^o + 0{,}8\frac{N^t}{100}, m^3/kg$$

$$V^o_{H_2O} = 0{,}111H^t + 0{,}0124W^t + 0{,}0161V^o + 1{,}24G_f, m^3/kg$$

$$V^o_g = V^o_{RO_2} + V^o_{N_2} + V^o_{H_2O}, m^3/kg$$

$$V_g = V_{RO_2} + V^o_{N_2} + V_{H_2O} + (\alpha - 1)V^o, m^3/kg$$

$$V_{H_2O} = V^o_{H_2O} + 0{,}0161(\alpha - 1)V^o, m^3/kg$$

2. Equations used in the calculation of the enthalpy of the air of the gases produced by combustion:

$$I_g = I^o_g + (\alpha - 1)I^o_{aire} + I_{cen}$$

$$I^o_{aire} = V^o(ct)_{aire}$$

$$I^o_g = V_{RO_2}(ct)_{RO_2} + V^o_{N_2}(ct)_{N_2} + V^o_{H_2O}(ct)_{H_2O}$$

3. Equations used in the calculation of thermal efficiency of the steam generator by the input and output method (Direct), since the losses in the Thermoelectric Power Plant due to equipment breakage are not being measured, therefore, it was carried out by the input and output method. (1)

For the method of inputs and outputs, it is necessary to evaluate the following:

- Heat that enters with the fuel.
- Heat coming in with the feed water.

- Heat that comes in for credits.
- Heat that comes out with the steam generated.
- Heat that comes out with continuous purging.
- Heat that comes out with the losses in the steam generator.

Efficiency was quantified using the following expression:

$$Eficiencia = \frac{Q_{aprovechado}}{Q_{suministrado}} \times 100\%$$

$Q_{suministrado}$: Total Heat Coming In:

$Q_{TE} = Q_f + Q_B + Q_{AA} + Q_R$

where:

Q_f: Heat entering with fuel, kJ/s

Q_B: Heat per Credits, kJ/s

Q_{AA}: Heat entering with feed water, kJ/s

Q_R: Heat entering through recirculated gases, kJ/s

$Q_B = BW_f \qquad B = (B_a + B_f + B_Z + B_m)$

where:

B: Credits, kJ/kg cq

W_f: Fuel mass flow, kg/s

B_a: Heat in the inlet air, kJ/kg cq.

B_f: Sensible heat in the fuel, kJ/kg cq

B_Z: Heat in atomizing vapor, kJ/kg cq

B_m: Heat supplied with moisture entering through air, kJ/kg cq

$Q_{aprovechado}$: Total Heat Output:

$$Q_{TS} = Q_V + Q_{Pc} + Q_P$$

where:

Q_V: Heat that comes out with the steam generated, kJ/s

Q_{Pc}: Heat coming out with continuous purging, kJ/s

QP: Losses in the steam generator, kJ/s

1. Calculation of the temperature of the gases at the exit of the furnace.

A large number of operational and design variables are involved in the calculation of heat transfer in steam generator furnaces. The main equation for the thermal calculation in the furnaces of steam generators is based on the application of the method of similarity of the thermal processes of the furnace and on the dimensionless equation proposed by A. M. Gurvich according to (5).

$$\theta_T^{"} = \frac{T_H^{"}}{T_a} = \frac{B_o^{0,6}}{MB_{\tilde{u}}^{0,3} + B_o^{0,6}}$$

Where:

$\theta_T^{"}$ —is the temperature relative to the furnace outlet (is the temperature of the combustion products at the outlet of the hearth in K; adiabatic temperature$\theta_T^{"} \leq 0{,}9$); $T_H^{"} - T_a -$

combustion; *Bo* - is Boltzman's number*;* $B_{\tilde{u}}$ —is the effective Buger number; *M* - is determined by the ratio of the relative position of the maximum flame temperature to the height of the furnace.

$$B_o = \frac{\varphi B (V_c)_{cp}}{\sigma_o \psi_{cp} F_{ct} T_a^3}$$

Then the temperature of the gases at the outlet of the is calculated by the equation:

$$\vartheta_H^{"} = \frac{T_a}{1 + M.B_{\tilde{u}}^{-0,3}\left[\frac{5{,}67.10^{-11}.\psi_{cp.}F_{ct}.T_a^3}{\varphi.B.(V_c)_{cp}}\right]^{0,6}} - 273$$

2. Calculation of NOx concentration:

The calculation is based on four main parameters of the combustion process in the kiln's active combustion zone (ACZ). These parameters are as follows: coefficient of excess air in ZCA, average temperature of the ZCA, heat flux reflected in the ZCA and the residence time of gases in the ZCA. (4)

The temperature in the active combustion zone determined by the equation:

$$\bar{T}_{ZCA} = T'_{ad}(1 - \bar{\psi}_{ZCA})^{0,25}(1 - R^{1+nR})$$

From the heat flux reflected in the active combustion zone, determined by the equation:

$$q_{ZCA}^{refl} = q_{ZCA}(1 - \bar{\psi}_{ZCA})r^2$$

From the coefficient of excess air in the active combustion zone, determined by the equation:

$$\alpha_{ZCA} = \alpha_{horno} + \Delta\alpha_{rec} = \alpha_{horno} + R\left(\alpha_{gasrec} - 1\right)$$

Of the time of residence of the gases in the zone of active combustion, determined by the formula:

$$\tau_{ZCA} = \frac{a.b - C_{ZCA}^{R,g}.\xi}{B.V_{gas}^{R,g}.(\bar{T}_{ZCA}/273)}$$

With these values, the concentration of NOx was calculated, in Excel taking the values of the previous calculations, by the following equation:

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

Analysis of the Results

The calculations were performed in Excel and the results presented in Table 4 were obtained.

NOx CONCENTRATION RESULTS FOR 100% CHARGE AND GAS RECIRCULATION VARIATION									
Tailcoat. Rec.	α_H	% Load	$\bar{T}_{ZCA}$	q_{ZCA}^{refl}	τ_{ZCA}	α_{ZCA}	C NOx ppm	CNOx mg/m3	Eficiencia
0	1,05	100	1814,70	0,98	0,04	1,05	528,04	633,65	86,39
0	1,05	75	1820,00	0,99	0,04	1,05	539,44	647,33	83,2
0	1,05	50	1824,76	0,55	0,04	1,05	239,57	287,49	80,23
0,1	1,05	100	1690,00	0,9	0,04	1,06	305,03	366,03	86,36
0,1	1,05	75	1694,86	0,9	0,04	1,07	312,12	374,55	83,17
0,1	1,05	50	1699	0,5	0,04	1,05	142,14	170,61	80,19
0,2	1,05	100	1584,14	0,83	0,05	1,06	176,98	212,37	86,34
0,2	1,05	75	1588,64	0,83	0,05	1,1	182,18	218,62	83,14
0,2	1,05	50	1592,68	0,46	0,04	1,05	84,59	101,51	80,15

As can be seen in Table 3, it was possible to determine the NOx concentration levels for different loads and recirculation ratio.

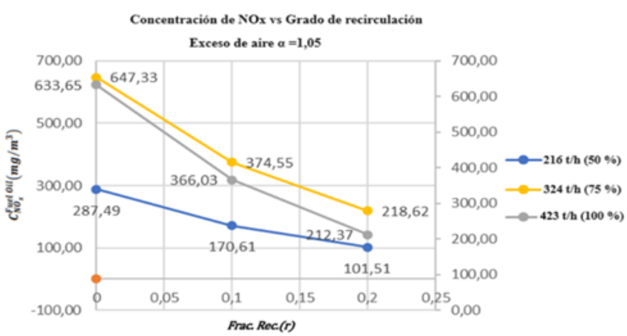

Figure 5. Nox Concentration Vs Degree of Recirculation.

From the results, it was possible to graph the variation in efficiency vs. degree of recirculation, with a coefficient of excess air of 5%.

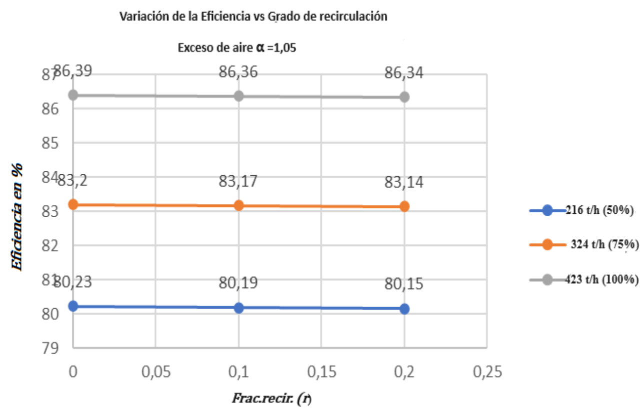

Figure 6. Variation In Efficiency Vs Degree of Recirculation

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