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ABATEMENT OF NO_X EMISSIONS AT BURNING FUEL OIL IN THE POWER BOILER

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ABSTRACT

This paper presents investigations towards finding new ways for the minimization of NOx emissions in the power boiler. These analyses were done in two directions: two stages of combustion into the furnace and a new system of re-circulating gases. The purpose of carrying out both analyses had the objective of diminishing the emission of nitrogen oxides during the combustion processes.

Both analyses were developed in a steam generator that currently working in the power plant “Villa de Reyes”, Mexico. This steam generator Mitsubishi Heavy Industries of 350 MW is equipped with four levels of tangential burners and it burns fuel oil (C_{23} $H_{37.29}$) during its operation. These analyses were carried out from the point of view of decreasing temperatures in the active burning zone (ABZ). The methodology is based on four main parameters related to combustion process in the furnace active burning zone (ABZ). Such parameters are the following: air excess coefficient in ABZ, average temperature in ABZ, reflected heat in ABZ and the residence time of combustion products in the ABZ.

Two stage of combustion is achieved by having three levels of burners in the bottom operate rich and the top level supply air only. The first volume burns 100% of fuel oil with 75% of air. In the second volume burns 0% of fuel and is introduced 25% of air. As a result, the decrease of NOx formation is up to 25% in comparison to current emissions.

On the other hand, the thermal calculation of furnace was done, and with the results it would be possible to change the place of recirculation gases to the hot air, changing the combustion processes and move the flame core position. The changes of the parameters to calculate NOx formation are the following: different thermal loads of the power boiler from 50%, 75%, 100% and maximum load. Different fractions of recirculation gases are introduced from 23% up to 61%. As result, it is possible to decrease NOx emission up to 50% in comparison to current emissions.

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 (NO_2) and nitrogen gemioxide (N_2O). Quantity of NO_2 and N_2O does not exceed 2 % [4] 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 [1]. 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]. The reactions of thermal NOx formation are characterized by high energy activation. Nitrogen oxides process occurs in a field with high temperatures exceeding 1800 K [4].

Formation process of NOx 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 [5].

The temperature in the active burning zone influences the NO_{th} formation process. Researches on kinetic model, developed by Roslyakov [5] have shown that temperature raise in active burning zone causes exponential NOx 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 [4, 5]. In boiler furnaces the residence time of combustion products is smaller, [3]. Hence, the equilibrium concentration is not reached.

NOMENCLATURE

V_{AIR}	[m^3/kg]	Volume of air in the ABZ
α_{VOL_1}	[-]	Coefficient of excess air in volume I
V_{AIR_ZONE1}	[m^3/kg]	Volume of air in zone I
V^0_{AIR}	[m$^3_{air}$ /kg]	Theoretical volume of air for burning a unit of fuel
α_{ABZ}	[-]	Coefficient of excess air in the ABZ
$\alpha_{FURNACE}$	[-]	Coefficient of excess air in the furnace
R	[m^3/kg]	Recirculation gases fraction
V_{CO_2}	[m^3/kg]	Volume of CO_2 in the combustion products
V_{H_2O}	[m^3/kg]	Volume of H_2O in the combustion products
V_{CO}	[m^3/kg]	Volume of CO in the combustion products
V_{H_2}	[m^3/kg]	Volume of H_2 in the combustion products
V_{N_2}	[m^3/kg]	Volume of N_2 in the combustion products
MW	[kg/kmol]	Molecular weight
ρ	[kg/m^3]	Density
V_{gas_VOL1}	[m^3/kg]	Volume of gases in the volume I
Q_{LIB_VOL1}	[kJ/kg]	Heat liberated in the volume 1
Q_{LIB_VOL2}	[kJ/kg]	Heat liberated in the volume 1I
Q_{VOL_1}	[kJ/kg]	Total heat in the volume 1
Q_{FUEL}	[kJ/kg]	Physical heat of fuel injected in ABZ
Q_{AIR}	[kJ/kg]	Heat brought in ABZ with hot air
Q_{REC}	[kJ/kg]	Heat brought in ABZ with gases of recirculation
$\psi_{AVERAGE}$	[-]	Absorptivity coefficient average of ABZ surfaces
T_{ABZ_VOL1}	[K]	Average temperature of gases in ABZ
n	[-]	Dependent factor on input method of the recirculation gases
q_{ABZ_VOL1}	[kW/m^2]	Absorbed heat flux in ABZ
B	[kg/s]	Fuel rate
A	[m^2]	surface
$q^{refl}_{ABZ\_VOL1}$	[KW/m^2]	Reflected heat flux in ABZ
τ_{VOL_1}	[s]	Residence time of gases in volume I
a	[m]	Furnace's width
b	[m]	Furnace's depth
$c^{R,g}_{ABZ\_VOL1}$	[m]	Height of zone I
ξ	[-]	Filling factor of ABZ with combustion products
$V^R_{gas\_VOL1}$	[m^3/kg]	Volume of combustion products with recirculation
$C^{fuel\ oil}_{NO_x}$	[ppm]	Nitrogen oxides concentration

OBJECT OF INVESTIGATION

For this investigation, a steam generator has been chosen; Mitsubishi Heavy industries (see fig. 1). Installed in the power plant "Villa de Reyes" in Mexico, this generator was designed to produce 1037.9 t/h of steam, pressure of 174.5 kg/cm^2 and temperature of 541 ^oC. The fuel is fuel oil, burned in tangential burners into the furnace, where the fuel/air is injected into the burners located in four levels.

The steam generator is equipped with re-circulating gas systems that are extracted after the economizer is injected in the bottom of the furnace. The fraction of re-circulating gas depends on the thermal load of the generator and it changes from 0.23 (thermal load 100%) up to 0.61 (thermal load 50%).

Figure 1. Thermoelectric Power Plant "Villa de Reyes"

The boiler has a system for re-circulating gases, where a certain amount of it is extracted after the air-heating stage (avoiding the gases to reach the stack) and is redirected back to the bottom of furnace. In the regenerative air-heater the air is warmed up. The excess air coefficient in the air-heater is 12 % due to external filtrations of air. The boiler is equipped with devices to measure the nitrogen oxide concentrations.

METHOD OF NO_X CALCULATION

In this part shows up the development of calculation method of NOx emissions in the steam generator's furnace of 350 MW at burning fuel oil using two stages of combustion. The furnace of steam generator was designed with four levels of burners to inject the fuel oil and the air into the furnace. To organize the combustion by two stages we need to change the distribution of the fuel through the levels of burners. For this purpose, 100% of the fuel is distributed in 12 burners of the three levels in the bottom. The 100% of air is distributed in 16 burners of total four levels. The burners of first three levels are injected by 100% of fuel and 75% of air. The level four this only fed by air.

Then in the chamber of combustion it is divided by two volumes (see figure 2) with different conditions of combustion (volume I and volume II).

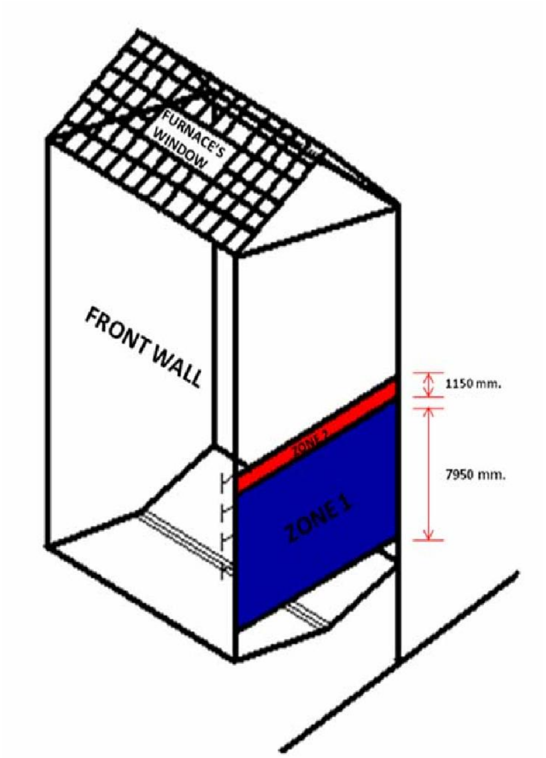


Figure 2 Distribution of volumes in the furnace of boiler.

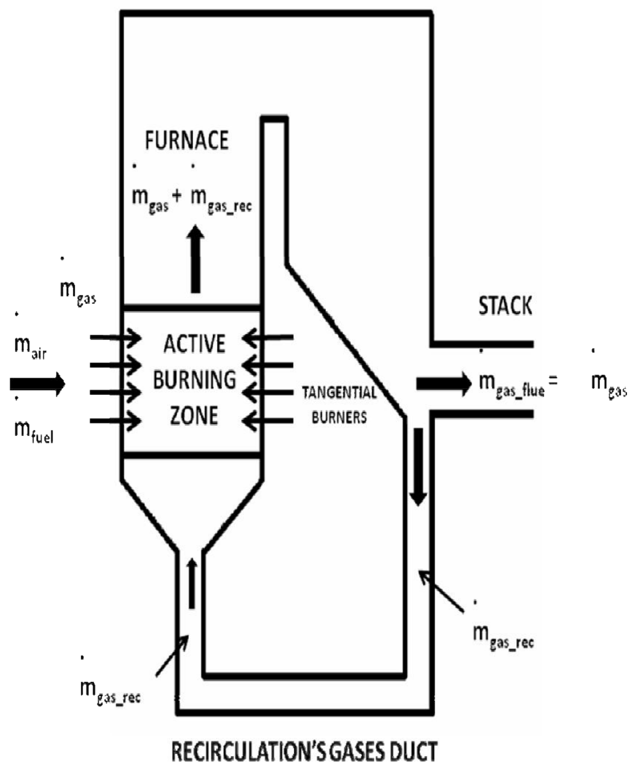
In the first combustion volume, it has a rich mixture, lacking oxygen for complete combustion. Under these conditions part of the hydrocarbons burns down until products of complete combustion and the rest to products of incomplete combustion.

The formation of nitrogen oxides in different volumes of the furnace depends on four physical parameters: average temperature in the active burning zone, the reflected heat flux, the excess air coefficient and the time of residence in this active burning zone.

EXCESS AIR COEFFICIENT

The balance of air was made in the furnace of the steam generator and is based on the figure 2, the participant gases are shown in the furnace, as well as the recirculation gases, in order to have a clear vision for the analysis of the excess air in the furnace.

It consider that of this flow rate of gases, it is necessary to analyze the volume of air that participates in the combustion coming from the recirculation gases and the other injected in different levels of burners.



Figures 3 Balance of gases in the steam generator of 350 MW

The two sources of air are schematized in figure 3 that enter to the active burning zone corresponding to the volume 1.

$$V_{AIR} = V_{AIR}\,|_{BURNERS} + V_{AIR}\,|_{RECIRCULATION} \qquad (1)$$

According to the definition of coefficient of excess air the following equation is obtained:

$$\alpha_{VOL\_1} = \frac{V_{AIR\_ZONE1}}{V_{AIR}^{0}} = \frac{3}{4}\alpha_{FURNACE} + \frac{1}{4}R\alpha_{FURNACE} - \frac{1}{4}R \qquad (2)$$

Therefore, it is observed that the coefficient of excess air in the active burning zone depends on the coefficient of excess air controlled in the operation of the furnace, and the amount of recirculation that is also controlled in the operation of furnace. Both variables are function of the load in which operates the steam generator.

VOLUME I

The volumes occupied by the combustion products in volume 1 are given by kg-mol of fuel, and it depends on the coefficient of excess air of the volume 1. To express the results in units of volume of the combustion gases in the volume 1, we take into account the densities, according to conditions of reference (pressure 1 bar, temperature 273K).

$$V_{CO_2} = \frac{1.105 \cdot \left(\alpha_{VOL\_1} \cdot 32.32 - 11.5\right) \cdot MW_{CO_2}}{\rho_{CO_2} \cdot 313.29} \tag{3}$$

$$V_{H_2O} = \frac{0.895 \cdot \left(\alpha_{VOL\_1} \cdot 32.32 - 11.5\right) \cdot MW_{H_2O}}{\rho_{H_2O} \cdot 313.29} \tag{4}$$

$$V_{CO} = \frac{\left[23 - 1.105 \cdot \left(\alpha_{VOL\_1} \cdot 32.32 - 11.5\right)\right] \cdot MW_{CO}}{\rho_{CO} \cdot 313.29} \tag{5}$$

$$V_{H_2} = \frac{\left[18.64 - 0.895 \cdot \left(\alpha_{VOL\_1} \cdot 32.32 - 11.5\right)\right] \cdot MW_{H_2}}{\rho_{H_2} \cdot 313.29} \tag{6}$$

$$V_{N_2} = \frac{(\alpha_{VOL\_1} \cdot 32.32) \cdot MW_{O_2} \cdot 3.293}{\rho_{N_2} \cdot 313.29} \tag{7}$$

The total volume occupied by the combustion gases in the volume 1 is represented by the following equation:

$$V_{gas}\,|_{VOL\_1} = V_{CO_2} + V_{H_2O} + V_{CO} + V_{H_2} + V_{N_2} \tag{8}$$

LIBERATED HEAT IN THE VOLUME I

In the volume 1 occurs two stages of combustion; the proportion in that it is developed each one depends on the quantity of present oxygen in function of the operation conditions and the percentage of the recirculation gases.

Balance of liberated heat in the two stages of combustion in the volume 1

During burning carbon is liberated 2869 MJ to form CO.

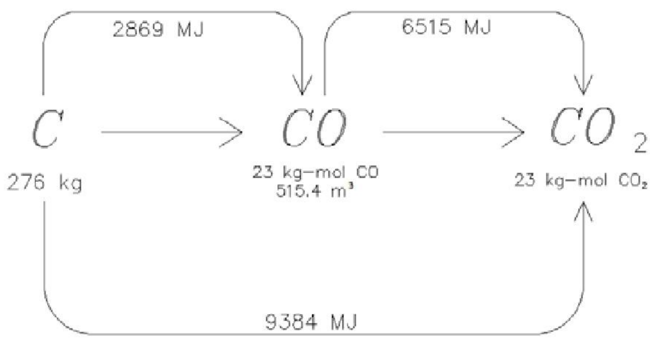


Figure 4 Balance of heat for carbon

For the combustion of the hydrogen we have the following relationship:

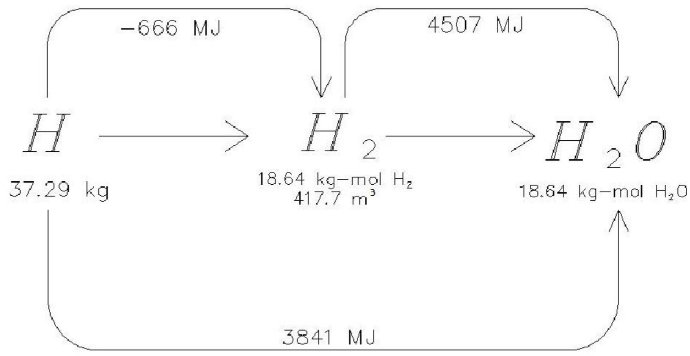


Figure 5 Balance of heat for hydrogen

This is, 666 MJ is needed to decompose the hydrogen of fuel. This balance of heat can be represented in a graphic way in the figure 5.

According to complete and incomplete products, the heat liberated in the volume 1, including the two stages of combustion, it was calculated by the following equation:

$$Q_{LIB\_VOL\_1} = \frac{n_{CO_2} \cdot 9384}{23} + \frac{n_{CO} \cdot 2869}{23} + \frac{n_{H_2O} \cdot 3841}{18.64} - \frac{n_{H_2} \cdot 666}{18.64} \tag{9}$$

This liberated heat was calculated on the basis of 1kg-mol of fuel. It will be enough with dividing the result of the previous equation by 313.29 so that this expression is function of the mass rate (kg / s) during the operation of the steam generator. Finally, the sum of heats in the Volume 1, it is represented by the following equation:

$$Q_{VOL\_1} = \frac{Q_{LIB\_VOL\_1}}{313.29} + Q_{AIR} + Q_{FUEL} + Q_{RECIRC} \tag{10}$$

where Q_{AIR} it corresponds to the heat that enters through the preheated air, Q_{FUEL} it corresponds to the enthalpy that contributes the preheated fuel and Q_{RECIRC} correspond to the enthalpy that provide by the recirculation gases injected in the bottom of the furnace. To calculate these heats we take the following equations and we consider the values of operation of steam generator according to the load.

ADIABATIC TEMPERATURE OF THE FURNACE

Using the thermodynamic tables of combustion products is determined the adiabatic temperature that corresponds to the volume I.

COEFFICIENT OF THERMAL EFFICIENCY

If the walls of the furnace are surrounded by waterwalls with different thermal efficiencies that cover the surfaces of the walls of furnace, the average value of the coefficient of thermal efficiency will be:

$$\psi_{AVERAGE} = \frac{\sum_{i=1}^{n} \psi_i \cdot A_{WALL.i}}{A_{WALL}} \qquad (11)$$

where $i = 1 \ldots n$ it is the number of areas of walls with different coefficients of thermal efficiency (ψ_i).

AVERAGE TEMPERATURE IN VOLUME I

The equation to calculate of the average temperature in the active burning zone in the volume I is [7,10]:

$$\overline{T}_{ABZ\_VOL\_1} = T'_{AD\_VOL\_1} \left(1\text{-}\psi_{\text{AVERAGE\_}VOL\_1}\right)^{0.25} \left(1\text{-}R^{1+nR}\right) \qquad (12)$$

where $\psi_{AVERAGE\_VOL\_I}$ it is the thermal efficiency average in the surfaces of active combustion.

FLUX OF HEAT IN THE VOLUME I

The heat flux in the zone of active combustion is given by:

$$q_{ABZ\_VOL\_1} = \frac{B \cdot Q_{VOL\_1}}{A_{TOTAL\_VOL\_1}} \qquad (13)$$

The fuel consumption B was obtained directly of the power plant.

FLUX OF REFLECTED HEAT IN VOLUME I

The reflected heat flux in the zone of active combustion is determined by the equation [8, 9]:

$$q^{refl}_{ABZ\_VOL\_1} = q_{ABZ\_VOL\_1}(1\text{-}\psi_{\text{AVERAGE\_VOL\_1}}) \qquad (14)$$

TIME OF RESIDENCE IN VOLUME I

The time of residence of combustion products in the zone of active combustion is determined by the equation [7, 8]:

$$\tau_{VOL\_1} = \frac{a \cdot b \cdot C_{ABZ\_VOL\_1} \cdot \xi}{B \cdot V^{R}_{gas\_VOL\_1} \cdot (\overline{T}_{ABZ\_VOL\_1} / 273)} \qquad (15)$$

Where ξ it is the coefficient of filling the ABZ with upward flow of combustion products and is equal to 0.70 for steam generators with tangential burners [6, 3]. When determining the height of ABZ for the volume I they should be obtained from their geometrical dimensions of ABZ in the steam generator.

NOx CONCENTRATION (PPM) IN VOLUME I

The general equation to calculate NOx emissions at burning fuel oil is [7, 8]:

$$C^{fuel\ oil}_{NO_x} = [24.3 \cdot \exp\left(0.19 \frac{\overline{T}_{ABZ} - 1650}{100}\right) - 12.3] \times [\exp(q^{refl}_{ABZ}) - 1]$$
$$\times [15.1 + 2.8(\alpha_{ABZ} - 1.09) + 73.0(\alpha_{ABZ} - 1.09)^2 + 72.3(\alpha_{ABZ} - 1.09)^3 - 131.7(\alpha_{ABZ} - 1.09)^4] \times \tau_{ABZ} \qquad (16)$$

TRENDS AND RESULTS

The steam generator burns fuel oil during its normal operation and it has instruments that measure the emissions of NOx. The method of current operation consists on the application of the recirculation gases in the bottom of the furnace and it is used as reference. Under these conditions and operating to partial loads: maximum load (MRC), 100%, 75% and 50% were obtained the emissions of NOx presented in the table 1.

Table 1 Data of NOx emissions from power plant.

Data from Power Plant	Unit	MRC	100%	75%	50%
NOx CONCENTRATION	ppm	**429**	**405**	**368**	**263**

RECONSTRUCTION OF RECIRCULATION GASES

With the universal method of recirculation gases have been obtained important reductions of NOx. In the reconstruction of the system of recirculation gases of this steam generator in the duct of hot air proposed by Jiménez García [7], a maximum reduction of NOx is 62.35%. The fundamental parameters that influence the NOx formation as well as the NOx concentration to partial loads are presented in the table 2.

Table 2 NOx emissions for a system of recirculation gases.

PARAMETER	Simbol	Unit	MRC	100%	75%	50%
AVERAGE TEMPERATURE IN ABZ	$\overline{T}_{ABZ}$	K	2024	2008	1893	1579.4
REFLECTED HEAT FLUX IN ABZ	q^{refl}_{ABZ}	MW/m^2	0.91	0.81	0.62	0.46
EXCESS AIR COEFFICENT IN ABZ	α_{ABZ}	-	1.06	1.06	1.07	1.243
RESIDENCE TIME OF COMBUSTION PRODUCTS IN ABZ	τ_{ABZ}	s	0.42	0.47	0.67	1.097
VOLUME OF ABZ WITH RECIRCULATION GASES	$V^{R,g}_{ABZ}$	m^3	14.3	14.6	17.1	19.91
HEIGHT OF ABZ	$C^{R,g}_{ABZ}$	m	9.54	9.77	11.5	13.33
NOx CONCENTRATION	C^{comb}_{NOx}	ppm	**344**	**315**	**225**	**99**

STAGED COMBUSTION

It was organized the two stages of combustion in the furnace of the steam generator. For this purpose 100% of the fuel is distributed in the first three levels of burners and in the fourth level air is injected only.

As a result of this distribution two combustion volumes are obtained inside the furnace. The calculation of the NOx concentration is carried out separately for each volume. From these obtained results was generated the total NOx concentration. The results of four fundamental parameters from staged combustion and the total NOx concentration generated by the furnace is show up in the table 3.

Table 3. Results of NOx emissions for staged combustion

PARAMETER	Simbol	Unit	MRC	100%	75%	50%
VOLUME I						
AVERAGE TEMPERATURE OF ABZ I	$\bar{T}_{ABZ}$	K	2063	2062	2071	2050
REFLECTED HEAT FLUX IN ABZ I	q^{refl}_{ABZ}	MW/m^2	0.78	0.70	0.53	0.45
EXCESS AIR IN THE ABZ I	α_{ABZ}	-	0.79	0.79	0.79	0.886
RESIDENCE TIME OF COMBUSTION PRODUCTS IN ABZ I	τ_{ABZ}	s	0.39	0.44	0.48	0.54
VOLUME II						
AVERAGE TEMPERATURE OF ABZ II	$\bar{T}_{ABZ}$	K	2393	2393	2468	2434
REFLECTED HEAT FLUX IN ABZ II	q^{refl}_{ABZ}	MW/m^2	1.15	1.03	0.78	0.57
EXCESS AIR IN THE ABZ II	α_{ABZ}	-	1.05	1.05	1.05	1.15
RESIDENCE TIME OF COMBUSTION PRODUCTS IN ABZ II	τ_{ABZ}	s	0.005	0.006	0.007	0.008
NOx CONCENTRATION	C^{comb}_{NOx}	ppm	388	361	293	198

The results obtained for the two stages combustion is observed that for the combustion of the volume I, the parameter that more influences on the formation of NOx it is the average temperature and the thermal efficiency. In the other case of the volume II the parameter that has bigger incidence on the formation of NOx is the time of residence. The following graph shows the NOx emissions of direct measurements in the power plant and the results obtained for two methods of NOx control to partial loads.

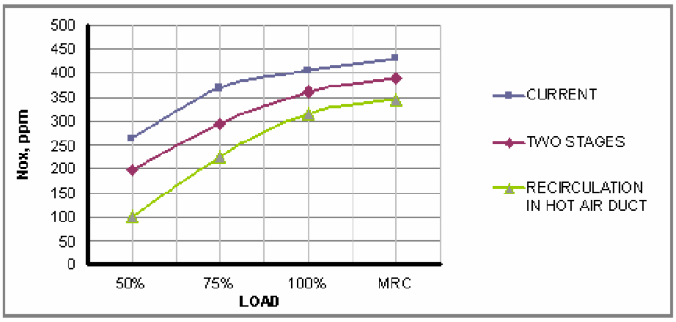


figure 6 Comparison of NOx emissions between: current operation, two stages and recirculation in hot air duct.

CONCLUSION

Applying the method of recirculation gases a maximum reduction of NOx of 62.35% is obtained in comparison to the method of current operation.

On the other hand, the staged combustion method applied to the steam generator achieves a minimum reduction of NOx of 10% for the Maximum Load, a reduction of 11% for 100% load and of 20.38% for 75% load. The maximum reduction of NOx is from 25% to 50% load. All the obtained results were compared with regard to the method of current operation. These results agree satisfactorily with the literature revision that reports a NOx decrease from 10 to 40% for staged combustion.

The recirculation method achieves a bigger decrease of NOx in comparison to the staged combustion. However, the advantage of the two stages combustion method is that it is not required additional expenses for its application.

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