Heat exchange and NO_X reduction in the 350 MW steam generator

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Abstract

In the first part of this paper the method of furnace calculation is based on the principle of similarity of furnace processes as well as the dimensionless equation suggested by A. M. Gurvich. This equation establishes the relationship between the dimensionless furnace exit temperature ($\theta''_{furnace}$) and the dimensionless terms: the Boltzmann number (B_0), the Buger number (Bũ) and the dimensionless term M. The second part reveals a study of NO_X formations in the furnace of a steam generator that currently works in the thermoelectric plant in "Villa de Reyes", Mexico. The analysis was carried out from the point of view of a new system of re-circulating gases into hot air in order to decrease nitrogen oxide formation in combustion process. The Mitsubishi Heavy Industries 350 MW steam generator is equipped with tangential burners and burns fuel oil during its operation. The thermal calculations in the furnace were conducted with the result that it would be possible to change the place of re-circulating gases by changing the process of combustion and moving the flames' core position. The changes to the operation parameters in order to calculate NO_X formations are as follows: different thermal loads to the power boiler were tested, from 25% to 100%; also, different fractions of re-circulating gases were tested, from 23% up to 61%. These analyses were done for the current system of recirculation, and for a new system of re-circulating gases. As a result, it is possible to decrease NO_X emissions by up to 50% in comparison with current emissions.
Keywords: thermal calculation, NO_X formation, combustion of fuel oil, furnaces, boiler.

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1 Introduction

The heat transfer in the furnaces of the power boilers is carried out mainly by radiation. The amount of heat transferred by convection is insignificant and in this type of furnace its calculation should not be taken into account. Monoatomic and diatomic gases (H_2,N_2,O_2) are diathermanous, i.e. transparent to thermal radiation. Triatomic gases (CO_2, H_2O, SO_2) possess the highest emissive power and absorptivity [14]. The heat transferred from gases towards the surface which receive radiation pass at the same time as the fuel burns into the furnace.

For this reason, the composition of the gases in the furnace; their temperature and radiation depends on the type of fuel. This method of burning changes throughout the flame. All of these processes together complicate the process of heat transfer and it challenges the development of an analytic method of calculation [1, 2].

The development of the method of thermal calculation in the boiler furnaces is based on the combined use of analytical and empirical investigations with the application of the theory of similarity for the analysis of the processes in the furnace. As a result, we have the empirical equation [1] which is based on the operational parameters of the characteristics of fuel, air and the supply of water. The geometrical dimensions of the furnace and the arrangement of burners determine the distinction between the nucleus of the flame and the temperature of the gases in the exit of the furnace [1, 2].

Moreover, in the combustion of fossil fuels, the products of combustion are identified as a severe cause of environmental damage. The main combustion products are carbon dioxide and water. Products of combustion in smaller quantities are nitrogen oxides [4]. Nitrogen oxides are a significant threat to the environment, and combustion systems are a major source of these pollutants [6]. Nitrogen oxides formed during the combustion process are designated as NO_X [4], either within the furnace or after discharging the flue gases into the atmosphere [10]. The nitrogen oxides (NO_X) formed in furnaces of the boilers represent the sum of nitrogen monoxide (NO), nitrogen dioxide (NO_2) and nitrous oxide (N_2O) [3]. The quantities of NO_2 and N_2O do not exceed 2%. In the last half of the twentieth century it was discovered that nitrogen oxides NO_X are a major factor of photochemical smog which enters the ozone of urban air [4].

The control of NO_X emissions is one of the most important elements in regulating [11]. Several NO_X reduction technologies have been proposed, such as staged combustion, re-burning, and in-flame NO_X reduction by using a low-NO_X burner [12]. This paper presents investigations towards finding new ways of minimizing NO_X emissions in power boilers. These analyses were done for the current system of re-circulating gases and for the proposed system of recirculation. The purpose of carrying out both analyses is with the objective of diminishing the emission of nitrogen oxides in the combustion process.

Nomenclature

θ°_{Hogar}	Dimensionless temperature of gases in the exit of the furnace;
$T^{\circ}_{Furnace}$	Temperature of combustion products in the exit of the furnace, K;
T_a	Adiabatic temperature, K;
B_o	Boltzmann number;
$B\tilde{u}$	Effective Burger number;
x_{burner}	Relative position of the core flame;
r_V	Parameter of composition of the gases that depend on the excess air and recirculation;
B_{calc}	Fuel consumption of the boiler at 100% load, kg/s;
φ	Coefficient of heat conservation in the furnace;
$(Vc)_{promedio}$	Average specific heat of the combustion products of 1 kg of fuel oil, kJ/kg;
$\varphi_{promedio}$	Average coefficient of thermal efficiency of water walls of the furnace;
$A_{paredes}$	Area of the water walls of the furnace, m^2;
G_{vl}	Flow of primary steam, kg/s;
G_{vII}	Flow of secondary steam, kg/s;
G_{purga}	Flow of purge, kg/s;
h_{vl}	Enthalpy of superheated steam, kJ/kg;
h_{aa}	Enthalpy of feeding water, kJ/kg;
$h^{'}$	Enthalpy of the water in the dome, kJ/kg;
$h^{''}_{vll}$	Enthalpy of the secondary steam in the entrance of the re-heater, kJ/kg;
$h^{'}_{vll}$	Enthalpy of the secondary steam in the exit of the re-heater, kJ/kg;
q_5	Loss of heat for external cooling of boiler;
ET	Thermal efficiency of boiler;
q_3	Loss of heat for incomplete chemical combustion;
q_4	Loss of heat for incomplete mechanical combustion;
Q_{rec}	Sensible heat of the recirculation gases, kJ/kg;
P	Pressure in the combustion chamber, MPa;
S	Thickness layer of gases that illuminate, m;
a	Burner's width, m;
b	Burner's depth, m;
c_{air}	Average heat capacity of air, MJ/m^3;
$c^{R,g}_{ABZ}$	Height of ABZ, m;
c_{gas}	Average heat capacity of combustion products, MJ/m^3;
c_m	Average heat capacity of water, MJ/m^3;
g	Amount of water supplied in ABZ, $\mathrm{m^3_{water}/m^3_{fuel}}$;
n	Dependent factor on the place of entrance of the recirculation gases;

q_{ABZ}	Absorbed heat flux ABZ, MW/m^2;
q_{ABZ}^{refl}	Reflected heat flux in ABZ, MW/m^2;
Q_{air}	Heat supplied in ABZ with hot air, MJ/m^3;
Q_{fuel}	Sensible heat of the fuel injected in ABZ, MJ/m^3;
Q_m	Heat supplied in ABZ by injection of water, MJ/m^3;
Q_{rec}	Heat supplied in ABZ with recirculation gases, MJ/m^3;
R	Fraction of the recirculation gases; m_{rg}^3/m_{fuel}^3;
$\bar{T}_{ABZ}$	Average temperature of gases in ABZ, K;
T_{ad}^1	Adiabatic temperature for incomplete fuel combustion in ABZ, K;
V_{air}^0	Theoretical air volume for burning 1 kg of liquid fuel, m_{air}^3/m_{fuel}^3;
$V_{ABZ}^{R.g}$	Volume of combustion products in ABZ including recirculation and water, m_{cp}^3/m_{fuel}^3;
α_{gas}^{rec}	Excess air coefficient of recirculation gases, [-];
β	Combustion efficiency, [-];
ψ_{ABZ}	Average thermal efficiency of water walls from the ABZ;
ξ	The filling factor of the ABZ with combustion products;
τ_{ABZ}	Time of residence, s;
$C_{NO_x}^{m}$	NO_x concentration, ppm.

2 Methodology of the thermal calculation

The main equation for thermal calculation of furnace boilers is the well-known equation [1], it relates to the dimensionless temperature of the gases in the exit of the furnace (θ''_{hogar}), the Boltzmann number (Bo), the Burger number ($B\tilde{u}$) and the parameter M, which considers the character of distribution of temperatures throughout the height of the furnace. The dimensionless temperature of the gases in the exit of the furnace is determined by the following equation [1, 2]:

$$\theta''_{hogar} = \frac{T''_{hogar}}{T_a} = \frac{Bo^{0.6}}{M \cdot B\tilde{u}^{0.3} + Bo^{0.6}} \tag{1}$$

where:
θ''_{hogar} is the relative temperature at the exit of the furnace.

For volumetric combustion furnaces, parameter M is determined by the relationship between the relative position of the maximum temperature of the flame and the height of the furnace. When burning fuel oil, the equation is [1]

$$M = M_0 \left(1 - 0.4 \cdot x_{burner}\right) \sqrt[3]{r_v} \tag{2}$$

where M_0=0.4 is for the combustion of fuel oil with the arrangement of burners installed in the walls or in the corners of the furnaces [1].

The number of Boltzmann determines the heat transfer by radiation and it is defined by the following equation [15]:

$$Bo = \frac{\varphi \cdot B_{calc} \cdot (Vc)_{promedio}}{5.67 \cdot 10^{-11} \cdot \psi_{promedio} A_{paredes} T_a^3} \tag{3}$$

In equation (3) $5.67 \cdot 10^{-11}$ is the coefficient of radiation of the blackbody, kW/m^2K^4.

The fuel consumption of the boiler is

$$B_{calc} = \frac{Q_{gv}}{Q_{disp} \cdot ET}, \; kg/s \tag{4}$$

The total quantity of useful heat of the boiler (Q_{gv}) from equation (4) is obtained with the following equation [1]:

$$Q_{gv} = G_{vl}(h_{vl} - h_{aa}) + G_{vII}(h''_{vII} - h'_{vII}) + G_{purga}(h' - h_{aa}), \; kJ/kg \tag{5}$$

The available heat in the combustion chamber of furnace *(Q_{disp})* is defined as the sum of the energy that enters including fuel, air and the recirculation of gases. The following is calculated using this equation:

$$Q_{disp} = Q_L + Q_{comb} + Q_{aire.ext} \quad \text{kJ/kg} \tag{6}$$

The coefficient of heat conservation in the furnace (φ) is calculated with

$$\varphi = 1 - \frac{q_5}{ET + q_5} \tag{7}$$

The average specific heat of the products of combustion of 1 kg of liquid fuel *$(Vc)_{promedio}$* of equation (3) is calculated with the following equation:

$$(Vc)_{promedio} = \frac{Q_{hogar} - h''_{hogar}}{T_a - T''_{hogar}}, \; kJ/kgK \tag{8}$$

Equations (3) and (8) are determined based on the calculations of the thermodynamic properties of the products of combustion like $T_a = f \quad (Q_{hogar})$ considering that Q_{hogar} is equivalent to the enthalpy of the products of combustion in the adiabatic process.

T''_{hogar} is the temperature of the gases in the exit of the furnace which is an unknown. To calculate the temperature T''_{hogar} the method of iterations is used.

For the calculation of the first iteration value $T''_{hogar} = 1323\ K$ is used for fuel oil, according to [1].

In equation (8) the heat in the oven (Q_{hogar}) is determined with the equation

$$Q_{hogar} = Q_{disp} \cdot \frac{100 - q_3 - q_4}{100 - q_4} + Q_{aire} - Q_{aireext} + Q_{rec}, \; {}^{kJ}\!/\!_{kg} \tag{9}$$

The enthalpy of the combustion products in the exit of the furnace (h''_{hogar}) using equation (8) corresponds to the temperature of gases in the exit of the furnace (T''_{hogar}).

To determine the relative temperature from the gases to the exit of the furnace θ''_{hogar}, employing the main equation (1) considering the need to define the effective Burger number ($B\tilde{u}$) before starting calculations. For this calculation, the equation is [1]

$$B\tilde{u} = 1.6 \cdot \ln\left(\frac{1.4 \cdot Bu^2 + Bu + 2}{1.4 \cdot Bu^2 - Bu + 2}\right) \tag{10}$$

In equation (10) is the Burger number for the products of combustion in the furnace of the boiler:

$$Bu = k \cdot P \cdot s \tag{11}$$

Finally equation (1) for the calculation of the temperature of gases in the exit of the furnace shows up in the following equation [1]:

$$T''_{hogar} = \frac{T_a}{1 + M \cdot B\tilde{u}^{0.3} \cdot \left(\frac{5.67 \cdot \psi_{promedio} \cdot A_{paredes} \cdot T_a^3}{10^{11} \cdot \varphi \cdot B_{calc} \cdot (V \cdot c)_{promedio}}\right)^{0.6}}, \text{ K} \tag{12}$$

3 Method of NO_x calculation

Glassman identifies three mechanisms for the formation of NO in combustion devices: the oxidation of atmospheric N_2 via a thermal NO mechanism, a prompt NO mechanism, and the oxidation of nitrogen-containing compounds in fossil fuels [13]. In the boiler furnaces all kinds of nitrogen oxides are formed. They are formed in a zone where fuel burns down and gas temperatures increase more than 1800 K. This zone is identified as the active burning zone [9]. In the works of [9], it has been shown that nitrogen oxide formations in the active burning zone (ABZ) depend completely on four major thermo-physical parameters. The parameters in the active burning zone are: excess air coefficient α_{ABZ}, average temperature, $\bar{T}_{ABZ}$, reflected heat flux, q_{ABZ}^{refl} and time of residence, τ_{ABZ}.

The most important parameter is the average temperature for combustion products in the active burning zone. This average temperature in function of R and n is proposed for power boilers:

$$\bar{T}_{ABZ} = T_{ad}^{I}\left(1-\bar{\psi}_{ABZ}\right)^{0.25}\left(1-R^{1+nR}\right) \tag{13}$$

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

$$T'_{ad} = \frac{\beta_{comb}PCI + Q_{aire} + Q_{rec} + Q_{comb} + Q_{agua}}{\beta_{comb}v_{gas}^{0}C_{gas} + 1.0161(\alpha_{quem} - \beta_{comb})v_{aire}^{0}C_{aire} + 1.24gC_{agua}} + 273 \tag{14}$$

C_{gas}, C_{air} and C_m are determined.

The average thermal efficiency coefficient of waterwalls for the active burning zone is determined with the equation:

$$\bar{\psi}_{ABZ} = \frac{\sum \psi_i A_i}{\sum A_i} \tag{15}$$

It is known that temperature provides the essential influence on nitrogen oxide formation. According to the definition, the average integral temperature in the ABZ is

$$\bar{T}_{ABZ} = \int_{0}^{\tau_{ABZ}} \left(\frac{T}{\tau_{ABZ}}\right) d\tau \tag{16}$$

The studies show that the maximum level of values for the concentration of nitrogen oxides does not depend on the average integral temperature but on the temperature of the highest gases in ABZ. However, it is not possible to calculate the highest temperature in ABZ. These are the average temperatures in ABZ and the reflected heat flux in the active burning zone. The reflected heat flux is determined under the equation:

$$q_{ABZ}^{refl} = q_{ABZ}(1-\bar{\psi}_{ABZ}) \tag{17}$$

The heat flux in ABZ is calculated:

$$q_{ABZ} = \frac{B(\beta Q_L + Q_{fuel} + Q_{air} + Q_{rec} + Q_m)}{A_{ABZ}} \tag{18}$$

Another important parameter of ABZ is the excess air coefficient, which is determined by the excess air in the burners and any additional air supplied by recirculating gases:

$$\alpha_{ABZ} = \alpha_{bur} + \Delta\alpha_{rec} = \alpha_{bur} + R(\alpha_{gas}^{rec} - 1) \tag{19}$$

The main source of nitric oxide emissions in combustion are the oxidation of molecular nitrogen in the post-flame zone (termed thermal NO), formation of NO in the flame zone (prompt NO), and oxidation of nitrogen-containing compounds in the fuel (fuel-bound NO) [5]. The investigations carried out in [9], have shown that the behavior of prompt NO_X formations from excess air coefficients at a constant temperature have an extreme influence. Thermal NO_X formations with the excess air coefficient have an exponential dependency.

It is suggested to use a fourth-degree polynomial to describe the influence of excess air in the final concentration of nitrogen oxides on exiting the active burning zone.

The residence time of combustion products in ABZ is determined by [9]

$$\tau_{ABZ} = \frac{a b c_{ABZ}^{R,g} \xi}{B V_{gas}^{R,g} (\overline{T}_{ABZ} / 273)} \tag{20}$$

ξ is equal to 0.7 for boiler furnaces with tangential burners.

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

$$\begin{aligned} v_{ZCA,rec,g} = \beta_{comb} v_{gh}^{0} + 1.0161(\alpha_{quem-}\beta_{comb}) v_{aire}^{0} + 1.24g + \\ + r[v_{gh}^{0} + 1.061(\alpha_{rec} - 1) v_{aire}^{0} + 1.24g] \end{aligned} \tag{21}$$

The height of ABZ depends on the geometrical sizes of the active burning zone and the relation of combustion product volumes in ABZ, given in as B and C:

$$c_{ABZ}^{R,g} = c_{ABZ} \frac{V_{ABZ}^{R,g}}{V_{ABZ}} \tag{22}$$

The volume of combustion products without recirculating gases and injected water into ABZ is

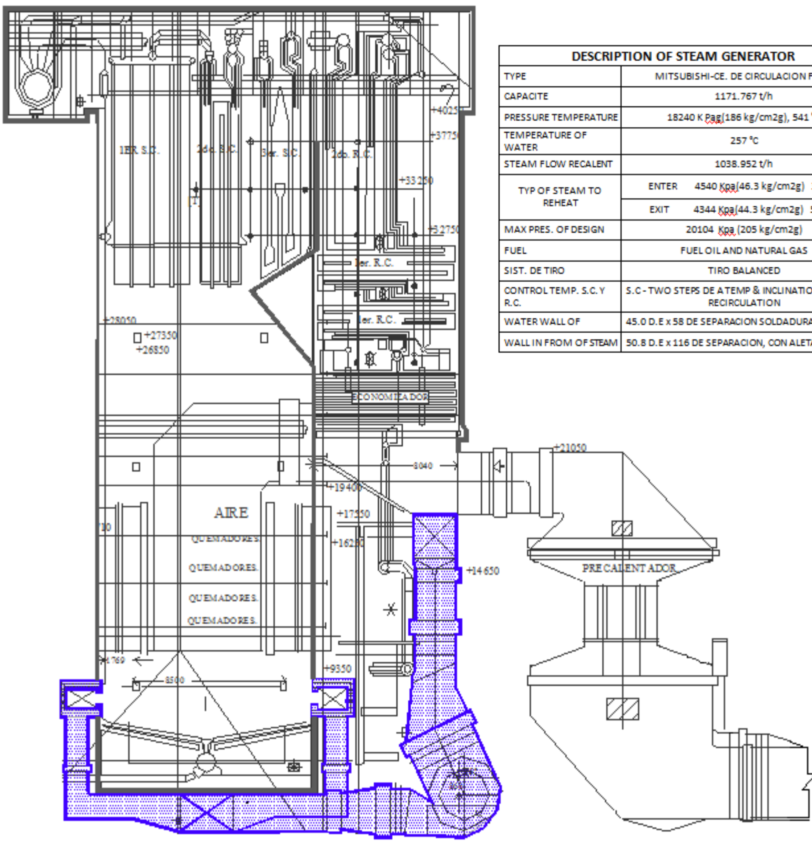
$$V_{ABZ} = \beta V_{gas}^{0} + 1.0161(\alpha_{bur} - \beta) V_{air}^{0} \tag{23}$$

The equation to calculate the nitrogen oxide concentrations (in ppm) in the combustion products of natural gas in the exit of ABZ:

$$\begin{aligned} C_{NO_X} = \left[24.3 \exp\left(0.19 \frac{\overline{T}_{ZCA} - 1650}{100} - 12.3\right)\right]\left[\exp\left(q^{refl}{}_{ZCA}\right) - 1\right] \bullet \\ \left[15.1 + 2.8(\alpha_{ZCA} - 1.09) + 73.0(\alpha_{ZCA} - 1.09)^2 + 72.3(\alpha_{ZCA} - 1.09)^3 + 131.7(\alpha_{ZCA} - 1.09)^4\right] \tau_{ZCA} \end{aligned} \tag{24}$$

4 Object of the investigation

For this investigation, a steam generator has been chosen; Mitsubishi Heavy industries and installed in the power plant named "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°C. The fuel employed is oil, burned in tangential burners into the furnace, where the fuel/air is injected into the burners located at four levels (see figure 1).



DESCRIPTION OF STEAM GENERATOR		
TYPE	MITSUBISHI-CE. DE CIRCULACION FZDA	
CAPACITE	1171.767 t/h	
PRESSURE TEMPERATURE	18240 K Pag(186 kg/cm2g), 541 °C	
TEMPERATURE OF WATER	257 °C	
STEAM FLOW RECALENT	1038.952 t/h	
TYP OF STEAM TO REHEAT	ENTER	4540 Kpa(46.3 kg/cm2g) 345 °C
	EXIT	4344 Kpa(44.3 kg/cm2g) 541 °C
MAX PRES. OF DESIGN	20104 Kpa (205 kg/cm2g)	
FUEL	FUEL OIL AND NATURAL GAS	
SIST. DE TIRO	TIRO BALANCED	
CONTROL TEMP. S.C. Y R.C.	S.C - TWO STEPS DE ATEMP & INCLINATION R.C.-GAS RECIRCULATION	
WATER WALL OF	45.0 D.E x 58 DE SEPARACION SOLDADURA P/FUSION	
WALL IN FROM OF STEAM	50.8 D.E x 116 DE SEPARACION, CON ALETA SOLDADA	

Figure 1: A 350 MW steam generator of with current re-circulating gas system [7].

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%). The recirculation system is used to control the temperature of reheated steam [7].

5 Main parameters in the furnace of the boiler

The most important parameters in ABZ that influence the NO_X formations are: average temperature in ABZ, the density of reflected heat flux in ABZ, the coefficient of air excess in ABZ and the time of residence in ABZ [6]. Table 1 shows the results of the calculations for the thermo-physical parameters and the NO_X concentrations for two constructions for recirculating gas systems [2].

Table 1: Thermo-physical parameters in ABZ of the 350 MW steam generator burning fuel oil.

PARAMETERS	100%	75.0%	50.0%
Recirculation	0.23	0.44	0.62
Heat available	44889	45743	46600
T_a adiabatic	2510	2549	2429
T_{zca} N=3.0 (K)	2007.8	1893.0	1579.4
T_{zca} N=6.5 (K)	2134.5	2130.6	1928.1
Excess air in the furnace	1.062	1.072	1.243
Reflected heat flux, ABZ	1397.0	1064.4	789.4
Reflected heat in ABZ	0.810	0.617	0.458
Time of residence N=6.5	0.442	0.592	0.899
Time of residence N=3.0	0.470	0.666	1.10
NO_X (ppm) current	**405.0**	**367.7**	**262.9**
NO_X (ppm) proposed	**315.2**	**225.2**	**99.3**

The recirculating gases enter the duct after the economizer is injected at the bottom of the furnace. For this construction, the authors of [3, 9] use a coefficient N=6 in the equation (1) in order to calculate the average temperature in ABZ. In this investigation we also analyze another proposed recirculation system with the injection of the gases in the duct of hot air (see figure 2).

Changing the place of injection of the recirculating gases does not influence the quantity and the temperature of gases in the exit of the furnace. For this reason, the proposed re-circulating system can be used to control the temperature of re-heated steam.

The analyses of NO_X formations were done for both the current system of recirculation and for the proposed system of re-circulating gases. These results are shown in figure 3.

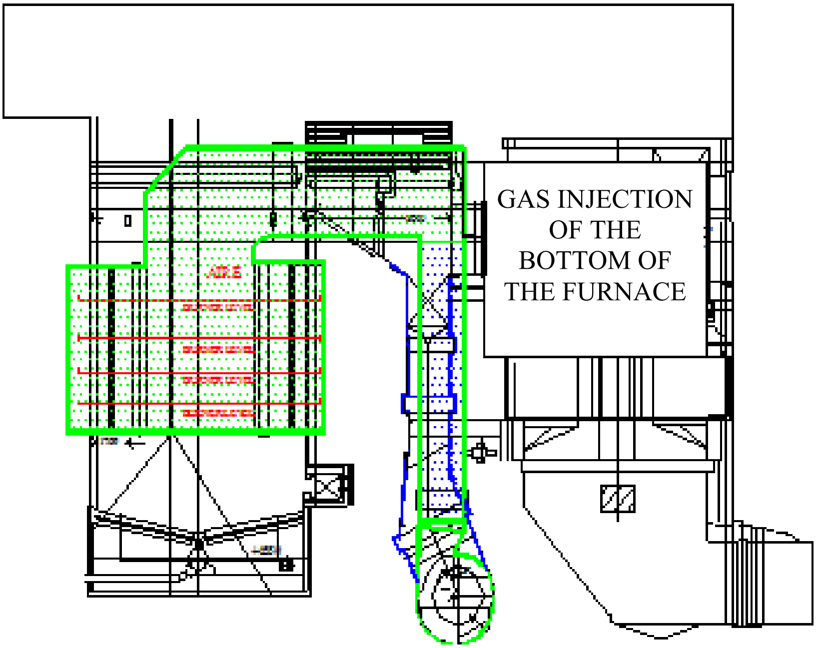


Figure 2: The 350 MW steam generator with the proposed recirculation gas system.

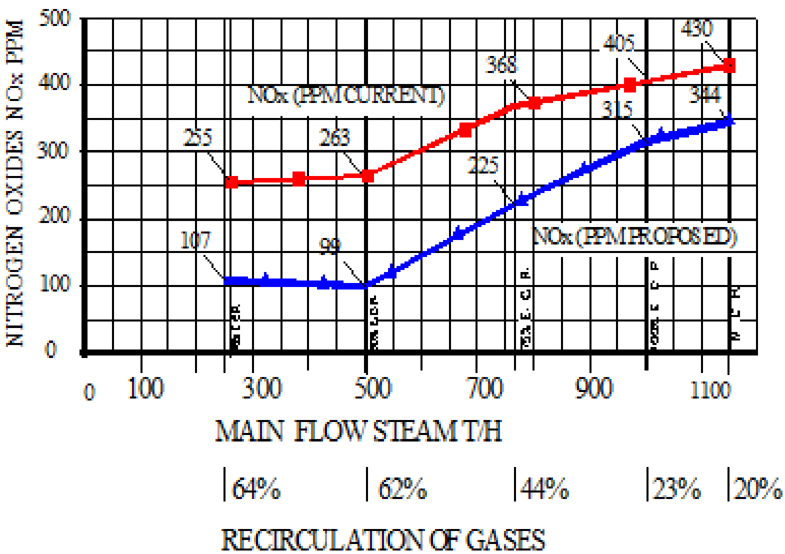


Figure 3: Concentration of NO_X in the 350 MW steam generator with the current and proposed recirculating gas system.

6 Conclusions

The method for NO_X calculations open the possibility to investigate the influence of different systems for the re-circulating gases in the furnace of a generator in order to verify which system is most effective.

For the concentrations of NO_X, applying the method developed for current re-circulating systems which are similar to the concentrations obtained by direct measurements in the power plant.

With the application of the proposed recirculation system it is possible to decrease the emission of NO_X from 405 ppm to 315.2 ppm with a load of 100% and from 255.2 ppm to 107.5 ppm with a load of 25%. According to the results obtained, it is possible to diminish the emissions of nitrogen oxide more than twice.

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