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Defining a Gas Turbine Performance Reference Database Model Based on Acceptance Test Results

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1. Introduction

With the growing participation of natural gas (NG) in power generation industry, a global worry about the effects of chemical composition changes on the behavior of gas turbines. A comparison of fossil fuels consumption used in power industry is shown in Figure 1 [1]. This figure represents a projection for the years 2003-2013 according to what is expected by the Mexican electric industry.

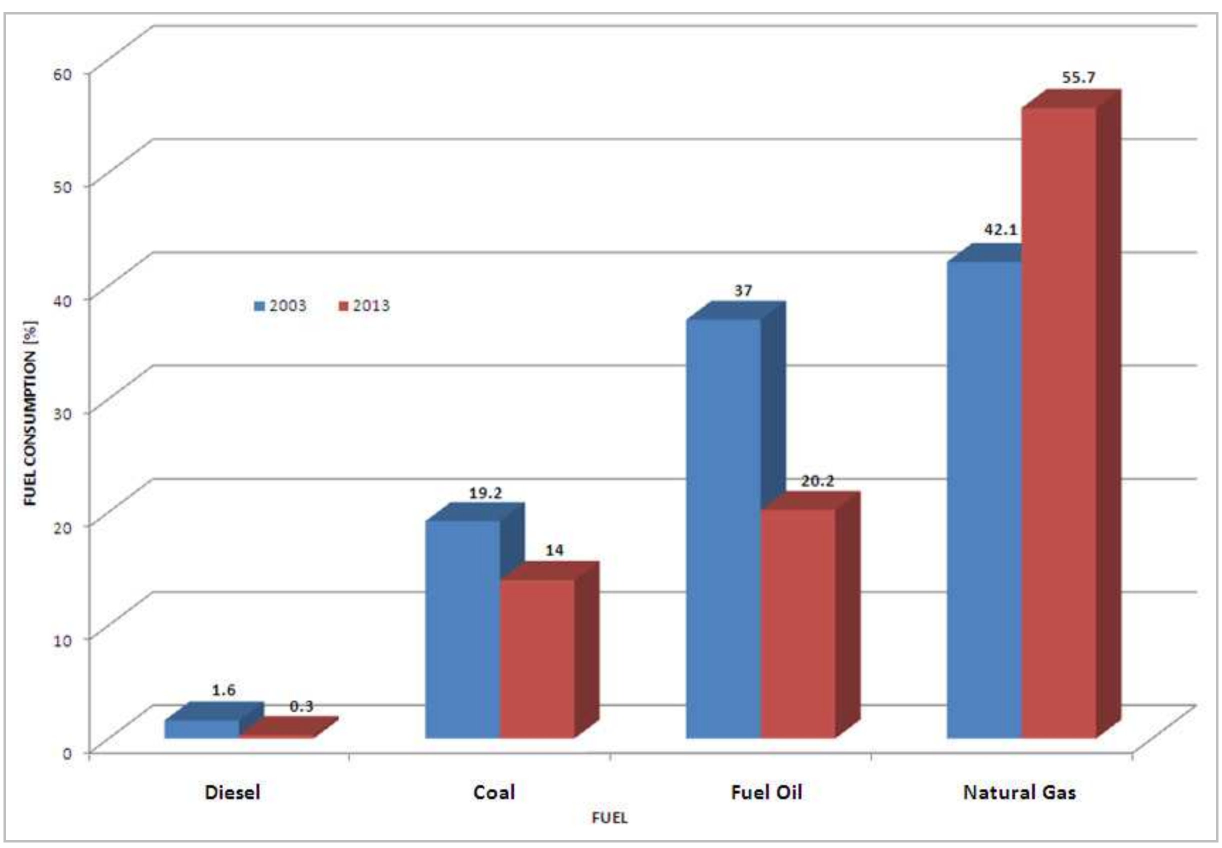

Fig. 1. Fuels Consumption in Mexican Power Industry.

The reduction of the fuel oil consumption observed in the previous figure is due to the process of substitution of this fuel by natural gas. This is because environmental reasons and techniques for incrementing the installed capacity through turbo gas plants and combined cycles based on natural gas.

As a sample of interest of the industry about this topic, it is possible to see that several technical papers related to this problematic, have been published during the last decade. All these works deal with gas quality, the variations on emissions, the increase in the noise levels and the consequences on gas turbine operation [2-10].

As departure point to evaluate the performance of turbogas power plants is analyzes, the increasing demand of electrical power in the world, as well as the necessity count with more modern and efficient electrical power plants orients to the design, installation and commercialization of new power plants which will be developed in harmony with the environment and promote energy saving. Like a behavior model of this phenomenon in Mexico is shown in Figure 2 where is presented the growth perspective to year 2016 of the national power sector in terms of generated gross energy.

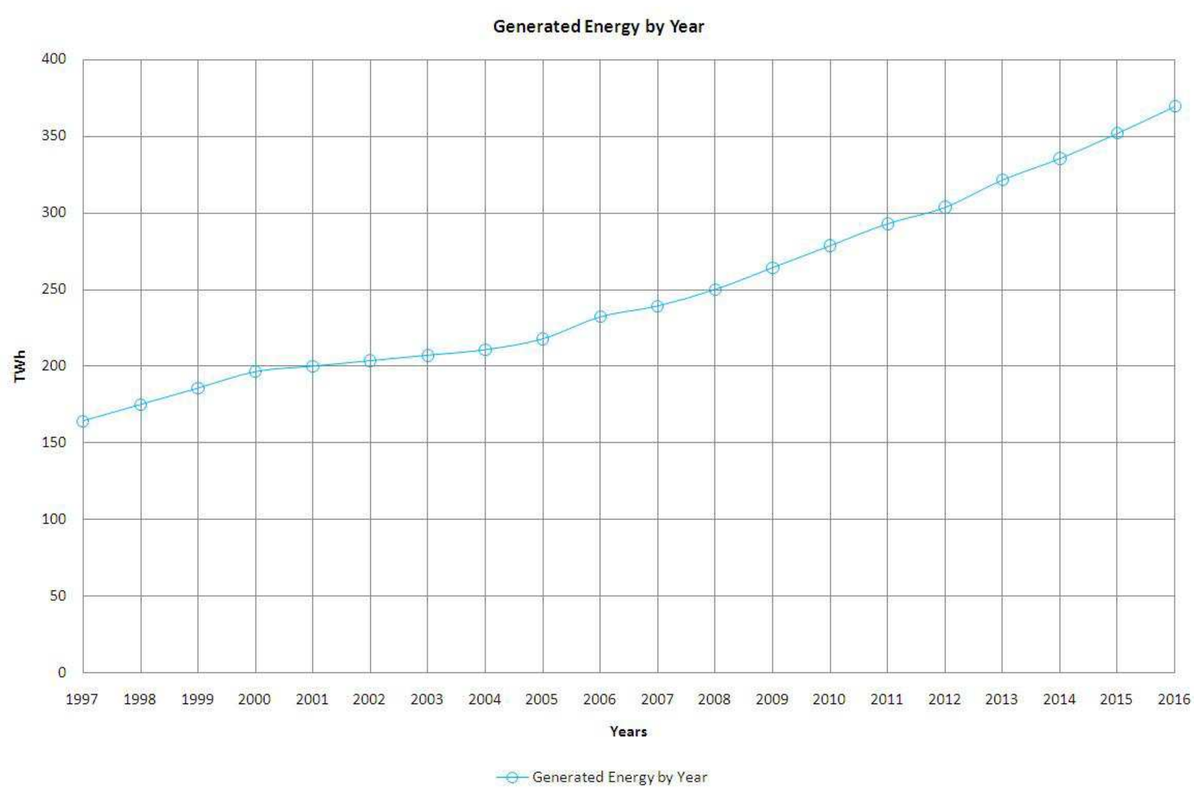

Fig. 2. Generated Gross Energy by Years in Mexico [11].

The growth expectation and modernization in terms of generation of electrical power in the central zone of Mexico gave rules to the Mexican Company of Electric Energy Generation (MCEEG) that operate in this zone to realize the acquisition of electrical power plants of distributed generation on strategic and critics zones around of Mexico city. Therefore MCEEG drove the installation of fourteen 32MW turbo gas electrical power plants impelled by aero derivatives turbines which burn natural gas.

As a result of the technical and administrative necessity of the MCEEG; combined with the effective national regulations in Mexico on terms of energetic production, it is realized collaboration on Mexican Electrical Research Institute (MERI) with the objective to develop this task during the works development until the commercial operation of each unit generation.

The main requirement to obtain the authorization certificate for beginning of the commercial operation of each one of fourteen power plants was the performance evaluation of each unit expressed in terms of average net power capacity, heat consumption rate, maximum noise levels and permissible levels of emissions. The MERI was to realize the behavior evaluation of these parameters through the determination of the average net power capacity, heat consumption rate, maximum noise levels and permissible levels of emissions from data collected during acceptance test of each turbo gas unit which was lead by a company specialized in the subject proposed by the supplier of the commissioning service of power plants and guaranteed by the MCEEG. As an additional product of the work carried out by the MERI, was develop a thermodynamics model based on real parameters obtained in each acceptance test which represents the initial operational state of the units and specifies the guidelines for a future trending monitoring system. The power plant has an aeroderivative turbine installed in simple cycle, operating with a cooling system (chiller) with effective capacity for a specific altitude and operation under any load regimen up to 32 MW.

2. Performance evaluation process

These tests are made on the final individual devices of each plant and integrate approaches to assessing the quality of the product. This is done in order to verify agreement between the guaranties and collected data on their performance under normal conditions of operation of the turbo unit, at different load levels with all its controls in automatic mode.

The goal of the tests is to verify if all devices of the open cycle turbo generator comply with the requirements established before, such as the guaranteed net capacity with the net unit heat consumption, guaranteed low level of noise and guaranteed pollutant emissions.

2.1 Power plant performance

The performance tests of Average Net Power Capacity (P_{NET}) and Heat Consumption Rate (Q_{RATE}) for 32MW turbo gas power plants were carried out in operation condition under base load with the air cooling system at turbine entrance running.

The measurements were developed with a combination of high precision instruments installed isolated and independent of the whole system (not connected to it). The measuring system implemented in the plant itself was also done. The measurements with high precision instruments were developed with instruments installed specifically for the performance test. Measurements of the plant are those made with permanent instrumentation of the plant, including measurements made by the flow meters from the gas station.

The net capacity (P_{NET}) was measured on the high side of the generator step-up transformer with the installed watt-hour meter (Digital-Multi-Meter DMM-B). The energy readings were recorded manually from the screen meter. The readings of energy (kWh) and the precise schedules (time) were used to calculate the average net capacity (P_{NET}) and net unit heat consumption (Q_{RATE}) carrying out the test using the following formulations:

$$P_{NET} = \frac{PM_{END} - PM_{START}}{\Delta t} \tag{1}$$

$$Q_{CONS} = \frac{m_{\tau}(Q_{ATM} + h_{CC} + h_{ATM})}{\Delta t} \tag{2}$$

$$Q_{RATE} = \frac{Q_{CONS}}{P_{NET}} \tag{3}$$

Where: PM_{END} and PM_{START} represented the power measurement at end and beginning the test (kWh), Δt is the time period of the test (h), Q_{CONS} is the heat consumption (kJ/h), m_{τ} is the mass of fuel used during the test period (kg), Q_{ATM} is Reference specific energy of fuel (kJ/kg), h_{CC} and h_{ATM} represented the specific enthalpy of the fuel (combustion chamber) and the reference specific enthalpy of the fuel (kJ/kg).

These tests results of the P_{NET} and Q_{RATE} should be corrected considering the variation between the current environmental conditions at the time of the test and the normal environmental conditions. Those are listed in Table 1.

PARAMETER
Fuel
Equipment Status (Load)
Atmospheric Temperature
Relative Humidity
Chiller Temperature
Altitude
Barometric Pressure
Low Calorific Power (Fuel)

Table 1. Basis Conditions of the Tests.

In order to meet the guaranteed values of performance in each turbo gas unit, it was necessary to adjust the values of (P_{NET}) and (Q_{RATE}) considering the base conditions. This was done by means of the use of correction curves by temperature, barometric pressure, relative humidity and fuel calorific value.

The Corrected Average Net Power Capacity (CP_{NET}) and The Corrected Net Unit Heat Consumption (CQ_{RATE}) are calculated by correcting the P_{NET} and Q_{RATE} values to the guarantee basis conditions; this is done following the correction methodology shown below:

$$CP_{NET} = \frac{P_{NET}}{F_{1P} \cdot F_{2P} \cdot F_{3P} \cdot F_{4P}} \tag{4}$$

$$CQ_{RATE} = \frac{Q_{RATE}}{F_{1HR} \cdot F_{2HR} \cdot F_{3HR} \cdot F_{4HR}} \tag{5}$$

Where: F_{1P}, F_{2P}, F_{3P} and F_{4P} represented the correction factor of measured power versus atmospheric temperature, humidity, barometric pressure and low calorific power (fuel) for corrected net capacity. F_{1HR}, F_{2HR}, F_{3HR} and F_{4HR} represented the correction factor of measured power versus atmospheric temperature, humidity, barometric pressure and low calorific power (fuel) for corrected heat consumption rate.

The correction factors are calculated by linear interpolation between the data points shown in the correction curves (see Figures 3, 4, 5 and 6). The data measured in each run test are averaged before entering the calculation of interpolation.

2.2 Noise level emissions evaluation

In Mexico, noise contamination produced by utilities is regulated by the Secretary of the Environment and Natural Resources ("SEMARNAT" by its initials in Spanish) [12]. This office establishes the policies and applicable regulations. On the other hand, the Mexican Official Standard ("NOM" by its initials in Spanish) [13] is the responsible for establishing maximum limits allowable for noise emissions produced by each industrial or power plant inside or outside the facilities.

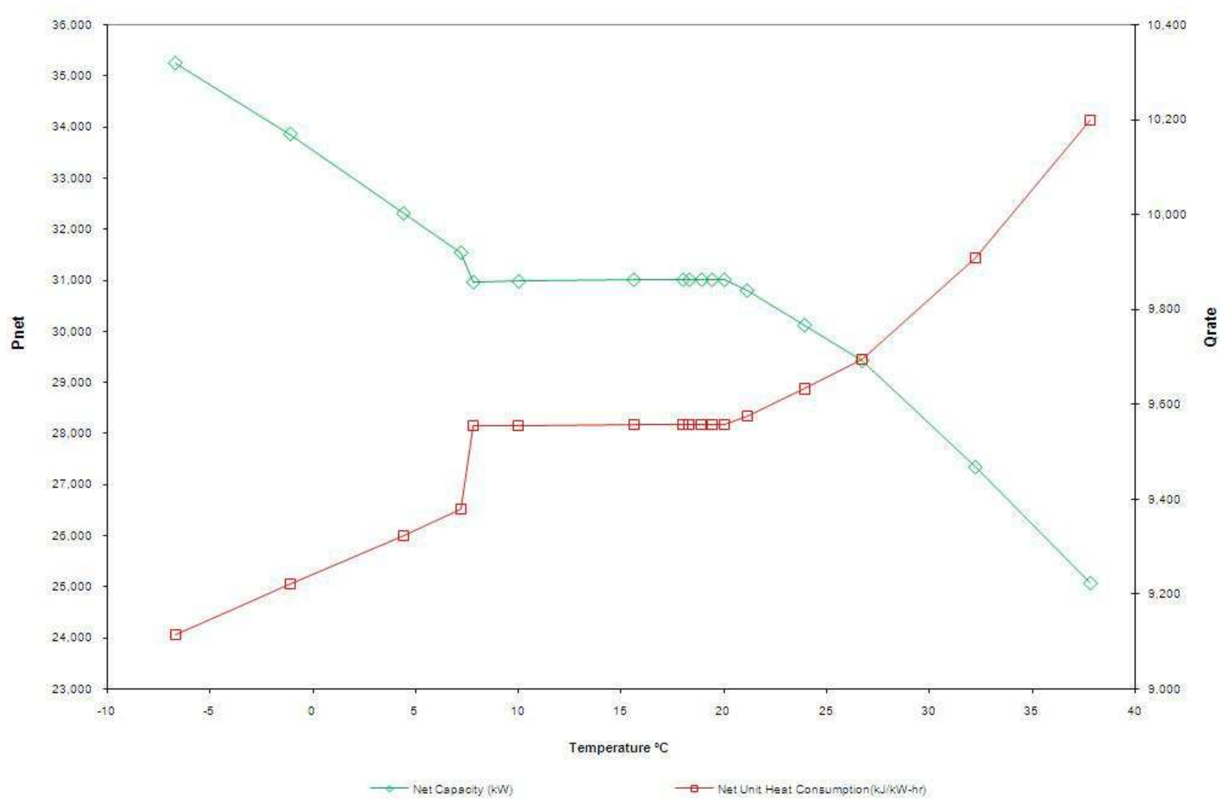

Fig. 3. Correction curve by temperature.

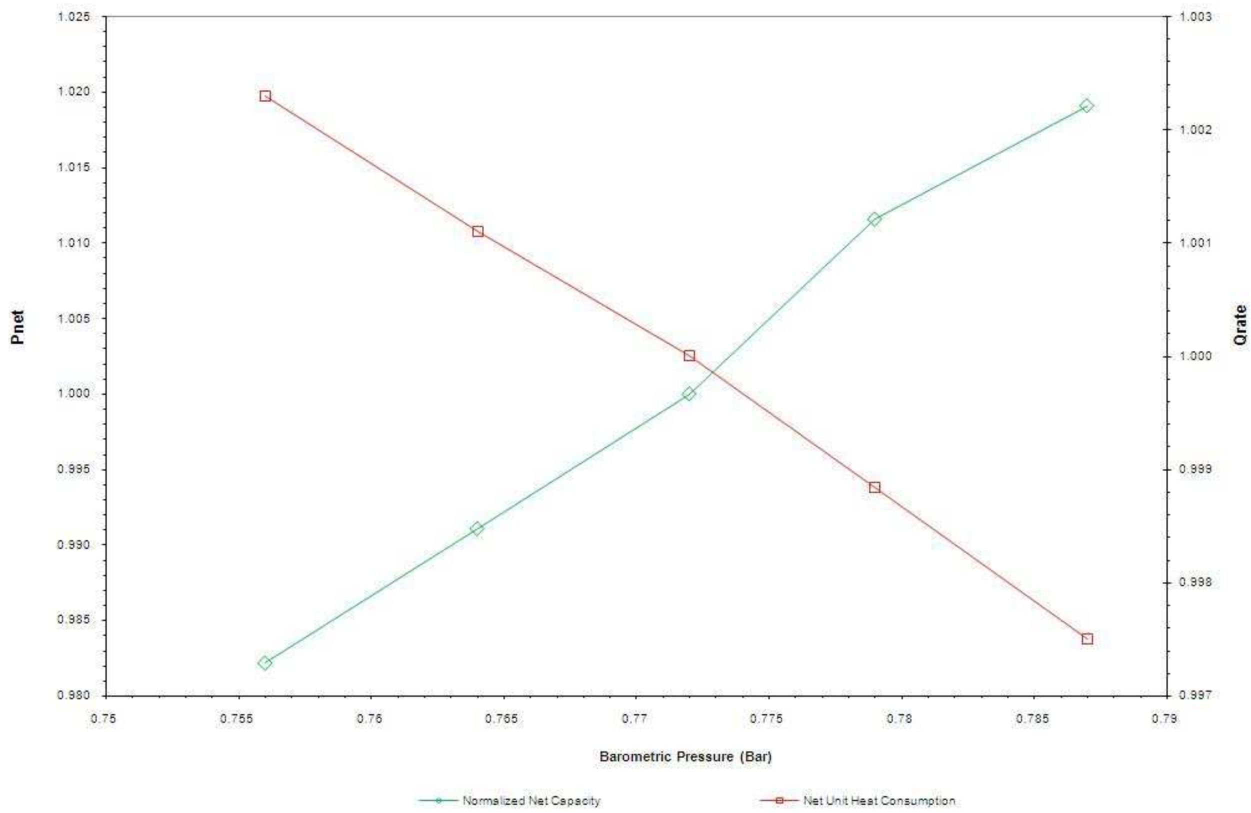

Fig. 4. Correction curve by barometric pressure.

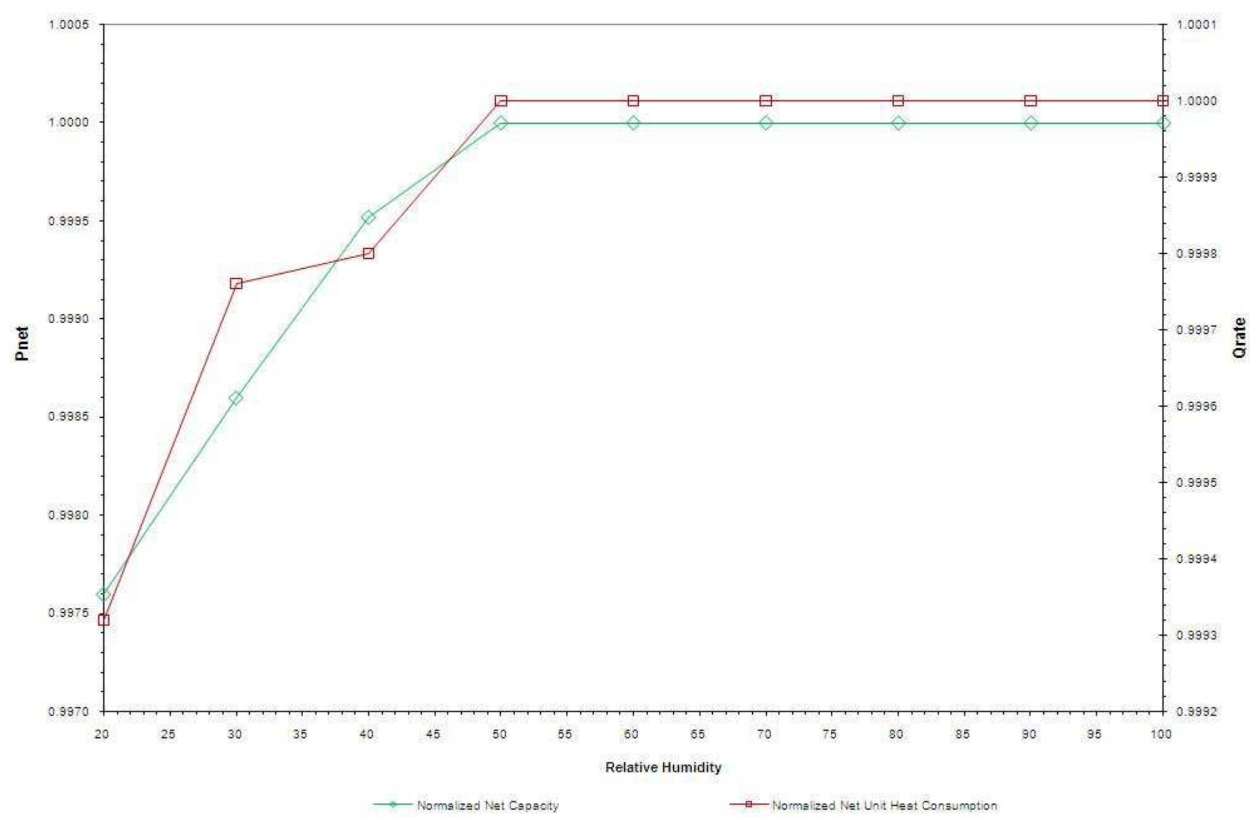

Fig. 5. Correction curve by humidity.

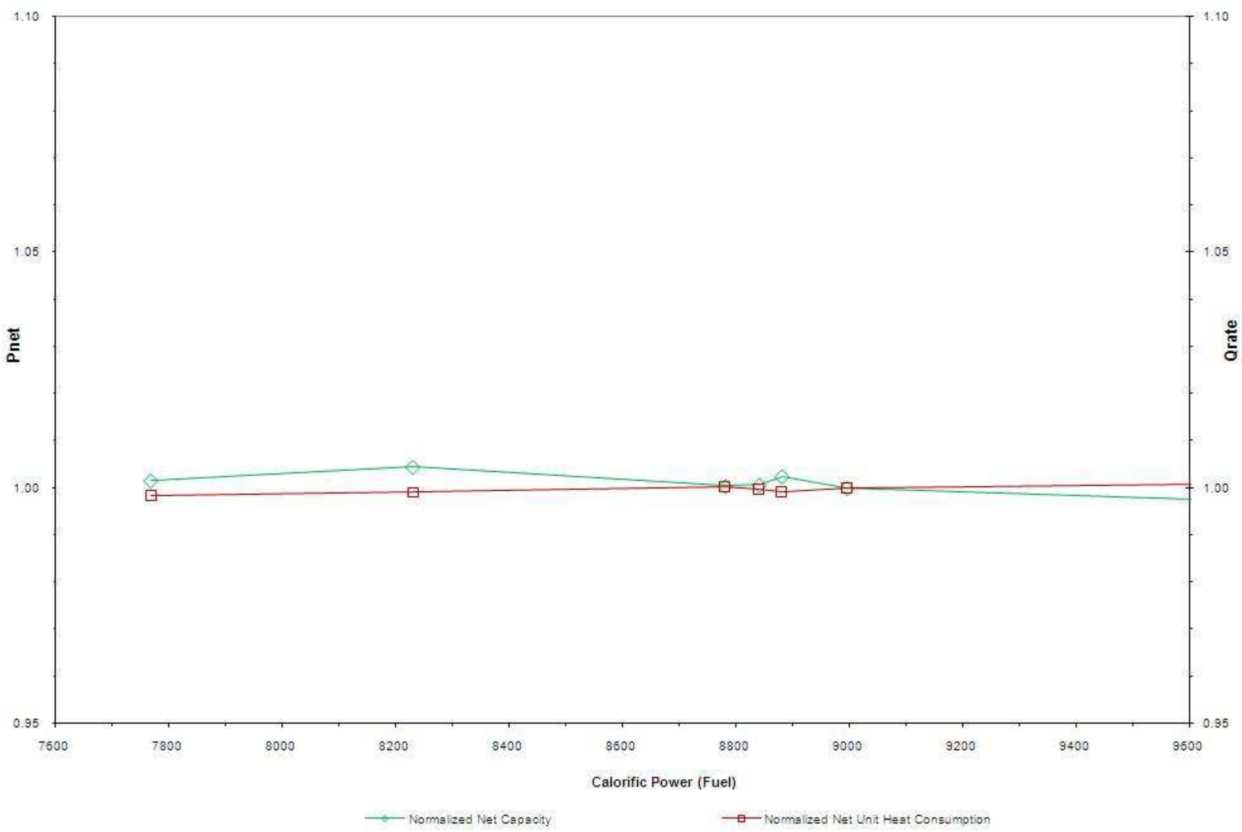

Fig. 6. Correction curve by calorific value of fuel.

In order to observe the previously described requirements, several activities were carried out during commissioning procedure of plants. Noise levels produced by some critical machines or equipments were obtained in near field (at the machine) and far field (around the facilities). All levels measured were below the comfort limits established by the standards, so they cannot reduce the quality of life of people living in the surroundings.

In order to get a correct measuring data processing acquired during far and near field noise evaluation, time intervals should be taken into account as well as minimum and maximum levels for each measuring point.

The equivalent sound level at each measuring point is determined through the mathematical expression (6):

$$N_{EQ} = 10\log\frac{1}{m}\left(\sum\nolimits_m 10\frac{N}{10}\right) \tag{6}$$

Then the means must be calculated from the measured values for each point by means of equation (7):

$$N_{50} = \frac{\sum_i^n N_i}{n} \tag{7}$$

In a similar way, from equation (8) the numerical values of standard deviation can be assessed for each point of the test:

$$\sigma = \frac{\sqrt{\sum (N_i - N_{50})^2}}{n-1} \tag{8}$$

It is also important to find out the noise level values that were present during more than 10% of total recording time through the equation (9):

$$N_{10} = N_{50} + 1.28817\sigma \tag{9}$$

Then corrected numerical values should be obtained from previous measurements:
Correction due to the presence of extreme values:

$$C_e = 0.9023\sigma \tag{10}$$

N_{50} average values from the fixed source and back noise:

$$\Delta_{50} = (N_{50})_{Source}(N_{50})_{Far} \tag{11}$$

Back noise correction:

$$C_f = -(\Delta_{50} + 9) + 3\sqrt{4\Delta_{50} - 3} \tag{12}$$

The numeric noise pressure value Nff from the noise source is obtained from equation (8):

$$N_{ff} = N_{50} + C_e \tag{13}$$

Finally, the last correction from back noise is used to determine the real numerical value of the noise source (equation 13)

$$N'_{ff} = N_{ff} + C_f \tag{14}$$

Where: N_{EQ} is the equivalent sound level (dBA), N is the fluctuant sound level (dBA), m is the total number of measurements, N_{50} is the mean of measured values (dBA), N_i is the sound level during certain time (dBA), n is the number of observations for each measuring point and σ is the standard deviation of measurements.

2.3 Emissions evaluation

Air quality and effects on the environment that produce the greenhouse gases emissions are of major importance for development of any country like Mexico. The nitrogen oxide emissions (NOx) from power generation equipment that uses technologies based on combustion cycles; are strictly regulated in order to develop monitoring and verification process of its generated atmospheric emissions during operation, according to Mexican Official Standards (NOM) which are compatible with the International Standards. For that previous reason, and based on the geographic location of the power plant facilities and according to Mexican Official Standards [14], this site is denominated like a critical zone (C_{ZN}) in Mexico because of high atmospheric pollution levels. This demonstrates the importance of establishing an emissions reference model that the plant generates during operation process.

The reference model was generated from the emission diagnosis develop to the power plant during the performance test at the end of the commissioning procedure. This model will be used as a reference basis for evaluation of emissions averages rates that the unit must handle during the history of operation.

Emissions testing and measurements were accomplished when the unit was operating at base load (100%) and at partial load of 75% with a 15% of O2.

The equipment used during testing consists of a fixed CEMS (Continuous Emission Monitoring System) which was calibrated prior and posterior to tests. This is done by comparing to a certified composition of reference gases found to be within the allowable deviation of +/- 3% [15].

Measurements were recorded manually from PC interface of the emission monitoring. Emissions were stored and endorsed every 110 minutes for both cases (full and partial load) observing a stable behavior of emissions.

After NOx measurements, some statistical calculations with the obtained data were done determining the mean and standard deviation for each load and observing the behavior of such values during load changes.

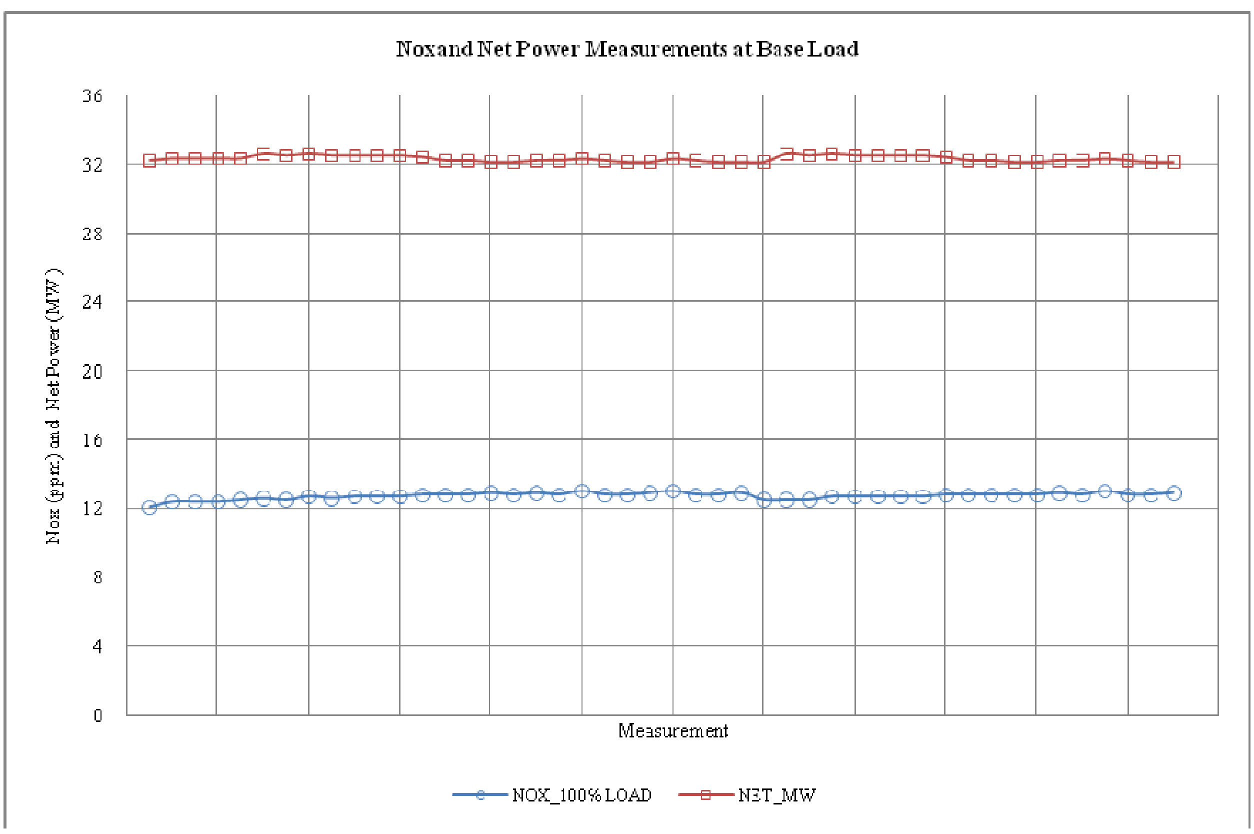

Fig. 7. NOx measurements (ppm) and Net Power (MW) recorded during test at 100% load.

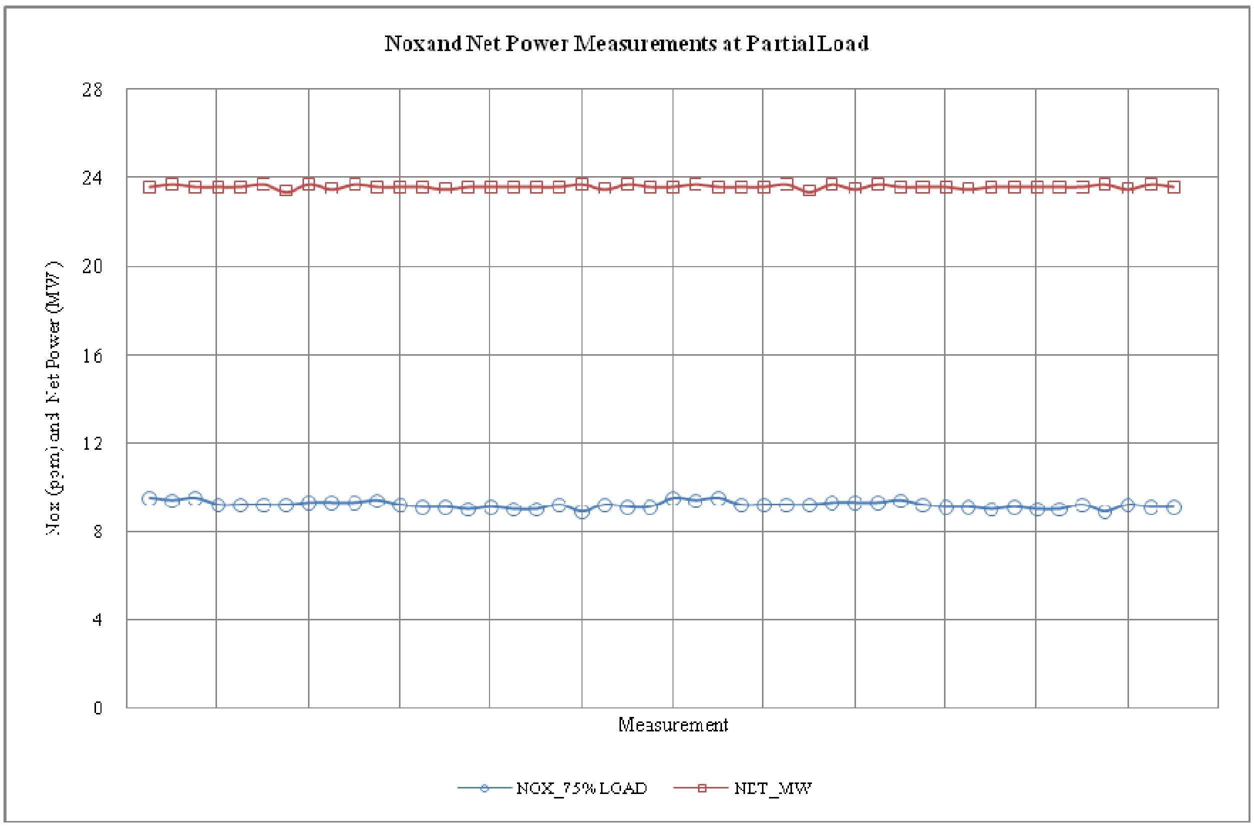

Fig. 8. NOx measurements (ppm) and Net Power (MW) recorded during test at 75% load.

3. Evaluation results

Once the tests, measurements, partial calculations and corrections of the mathematical models have been completed, it is come to make an evaluation of the results obtained with respect to the reference values guaranteed by the manufacturer and with the applicable standards for each parameter.

Firstly the results evaluation on terms of Average Net Power Capacity (P_{NET}) and Net Unit Heat Consumption (Q_{RATE}) at base load and partial load (75 percent) it is realized.

According to the values provided by the manufacturer and based on the average basic operations conditions for each one of the fourteen power plants, the guaranteed reference values of Average Net Power Capacity (P_{NET}) and Net Unit Heat Consumption (Q_{RATE}) are shown in the table 2:

PARAMETER	GUATANTEE VALUE	UNITS
Guaranteed Net Capacity	31,368	kW
Guaranteed Net Unit Heat Consumption	9,545	kJ/kWh

Table 2. Performance guarantees.

A comparison summary on term of Guaranteed Average Net Power Capacity with respect to the obtained results in test for fourteen power plants at base load and partial load are shown in Figures 9 and 10.

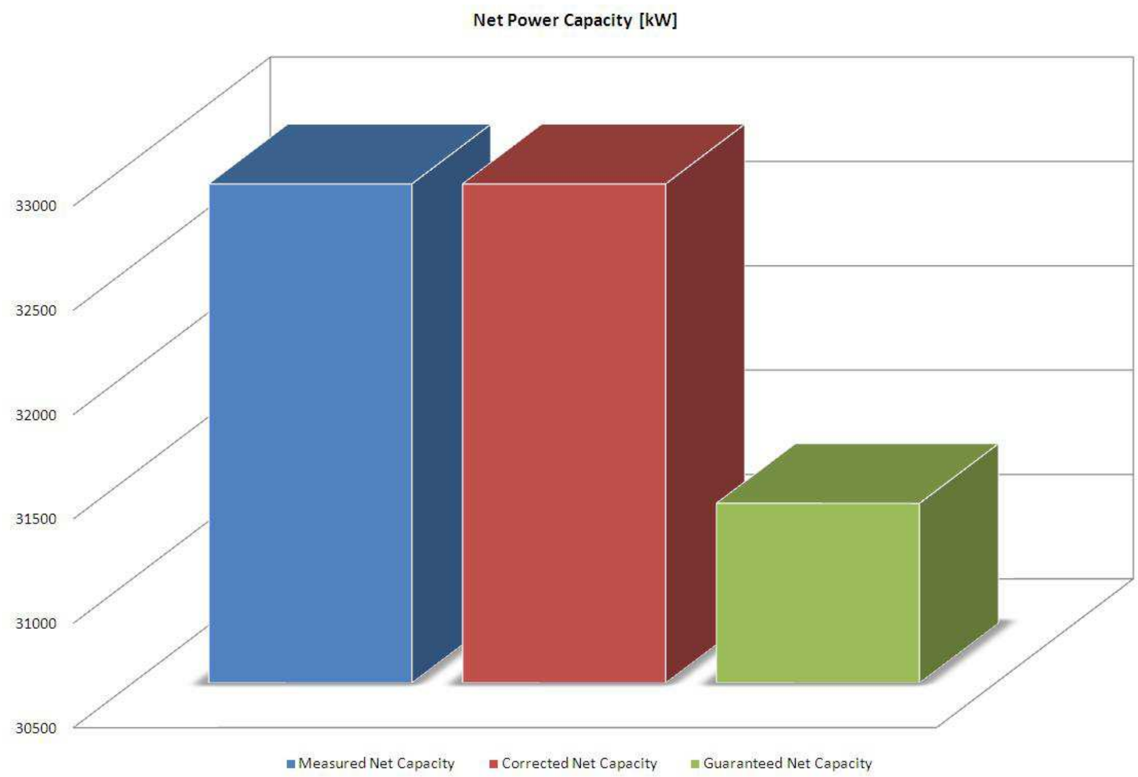

Fig. 9. Average Net Power Capacity comparison test results vs. guaranteed values of the units at base load.

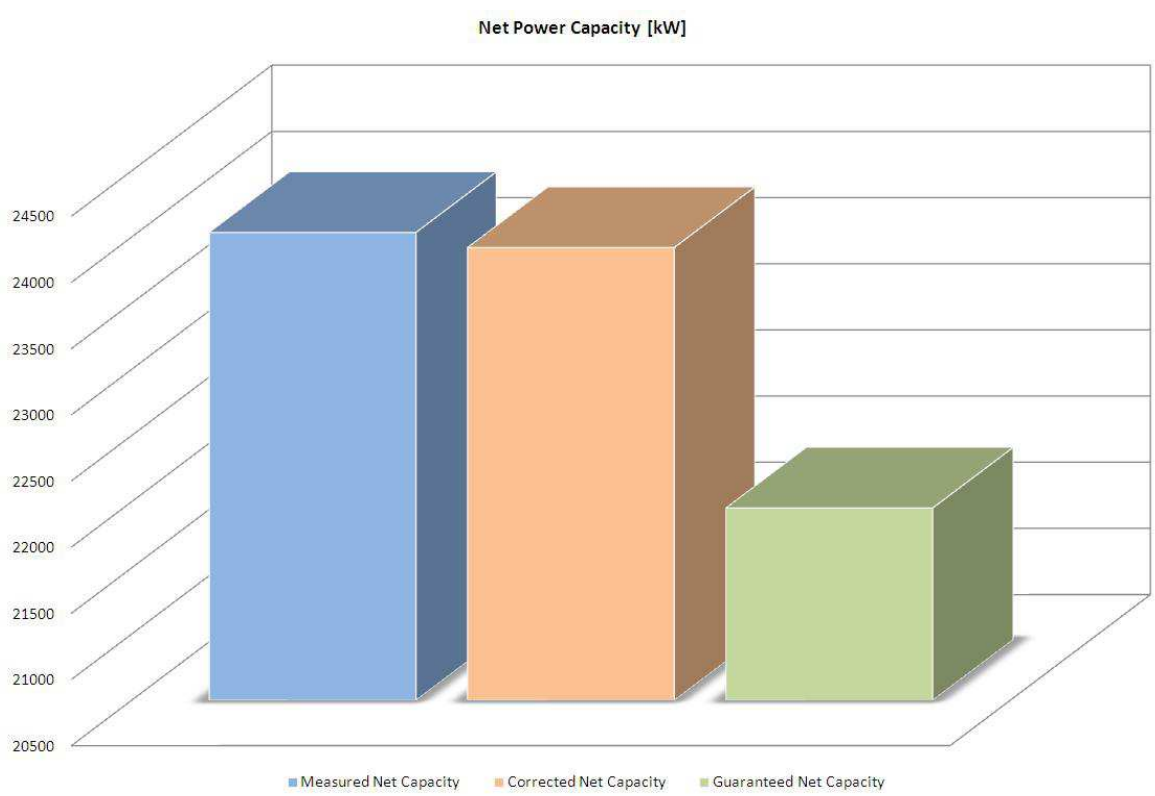

Fig. 10. Average Net Power Capacity comparison test results vs. guaranteed values of the units at partial load (75 percent).

Similar form to a the previous summary now appears a comparison in terms of Guaranteed Net Unit Heat Consumption with respect to the obtained results in test for fourteen power plants at base load and partial load are shown in Figures 11 and 12.

In the other hand the NOx measurements, some statistical calculations with the obtained data were done determining the mean and standard deviation for each load (100% and 75%) and observing the behavior of such values during load changes. Figure 13 shows graphically the recorded deviations.

Figure 14 shows a comparison of reference values established by the national standards [15] an international standards [16], the guaranteed value by the manufacturer [17] and the mean values obtained during the tests.

Once obtained the near and far field noise pressure levels during the test for the fourteen power plants, they were compared to the reference value found in the Mexican standard [13] as shown in Figure 15. From that standard it can be seen that the reference value is higher than the measured one guaranteed by the manufacturer.

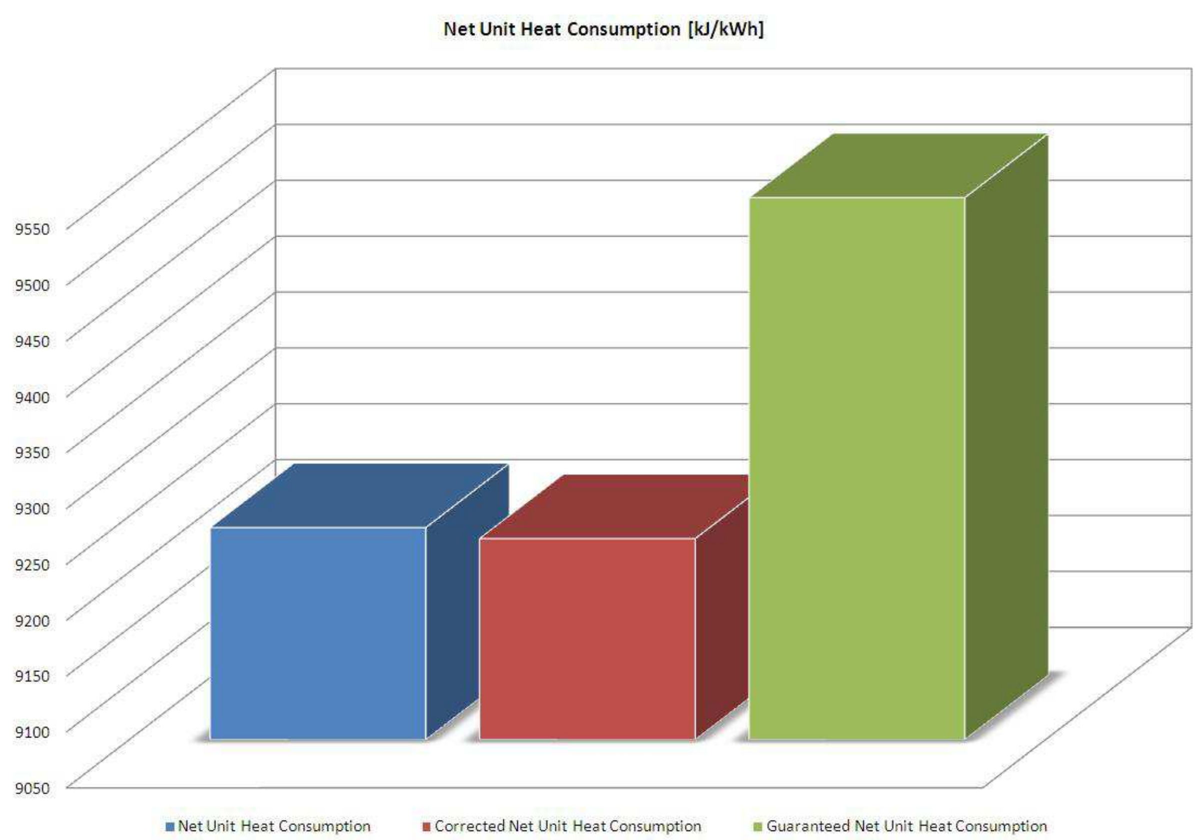

Fig. 11. Net Unit Heat Consumption comparison test results vs. guaranteed values of the units at base load.

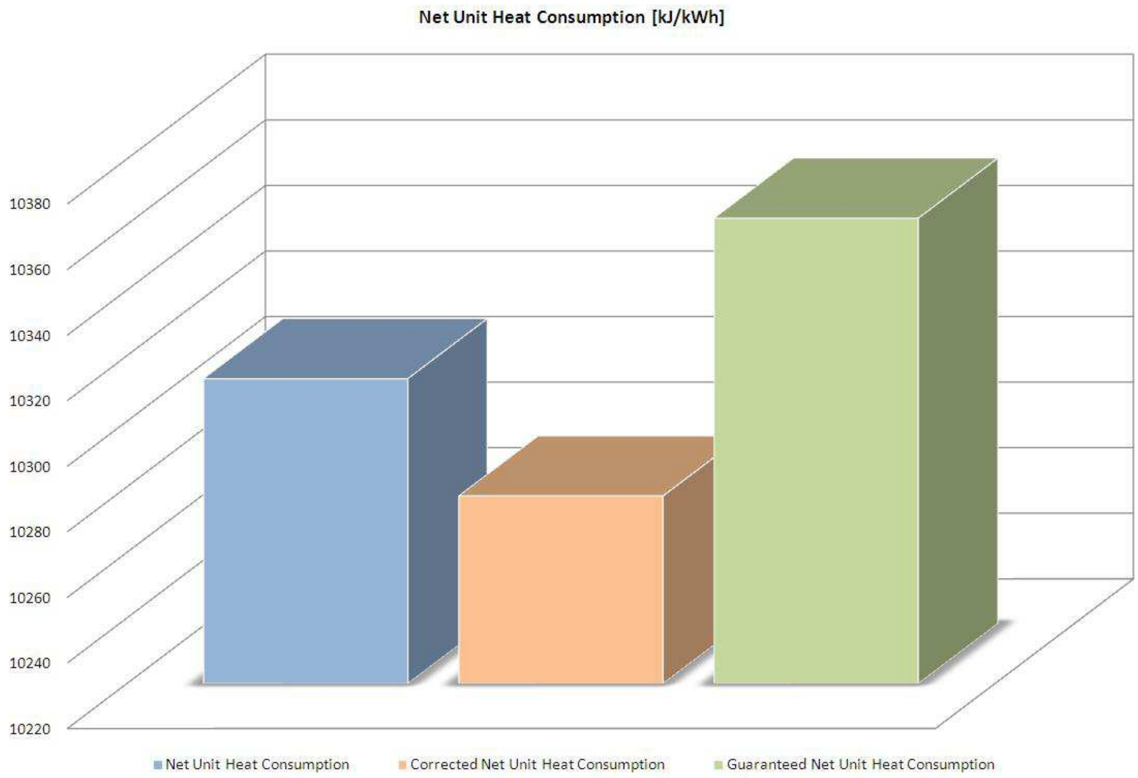

Fig. 12. Net Unit Heat Consumption comparison test results vs. guaranteed values of the units at partial load (75 percent).

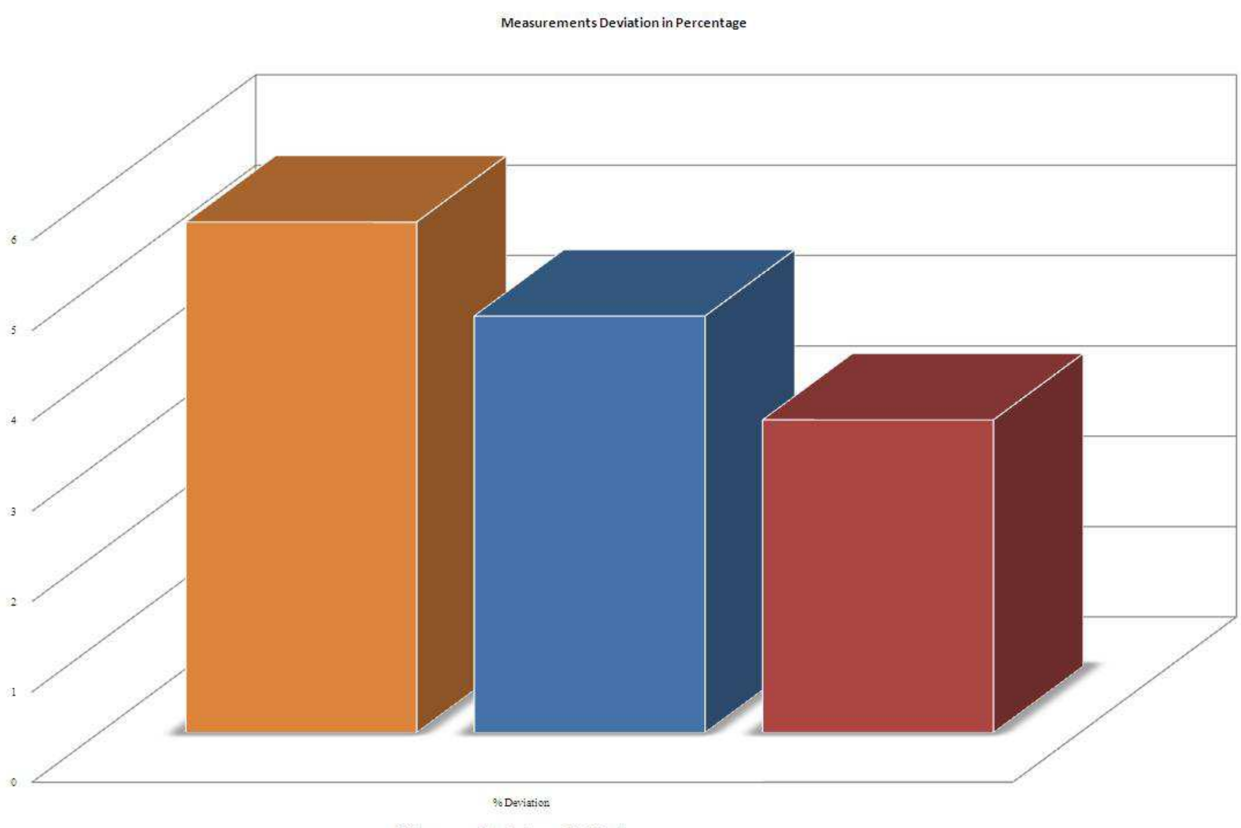

Fig. 13. NOx measurement deviation in percentage obtained during tests.

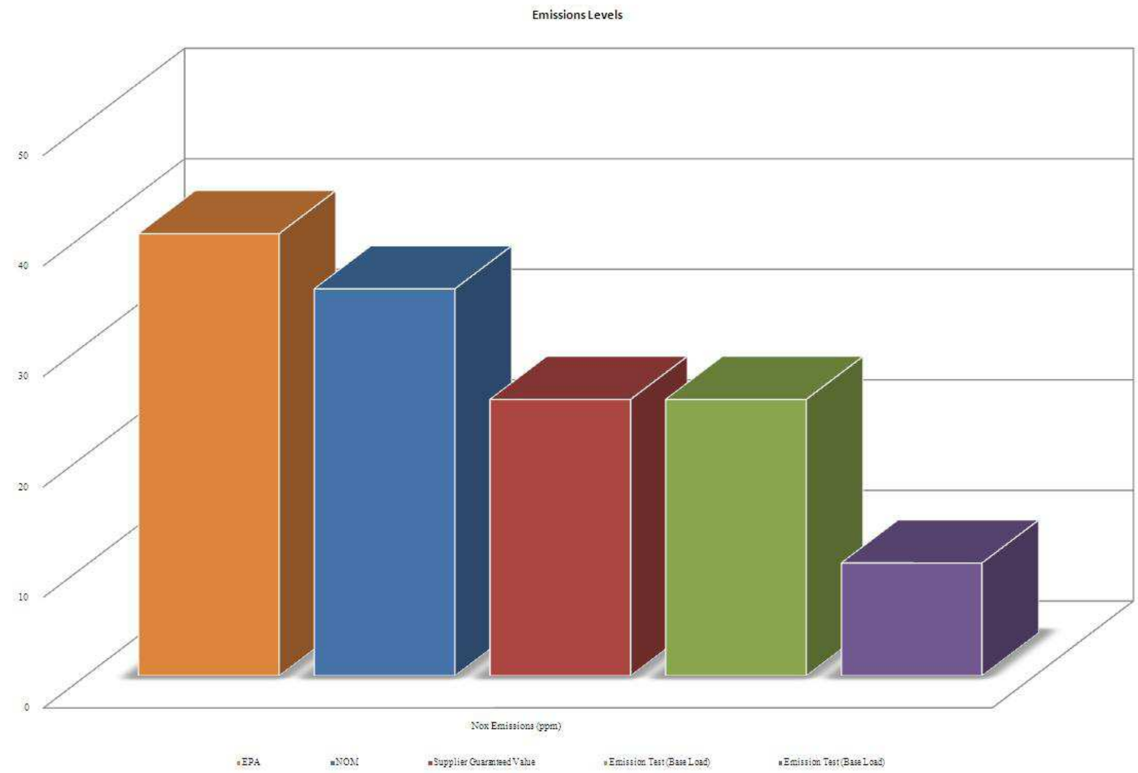

Fig. 14. Comparison of the results obtained during the tests with regard to national and international standards and guaranteed values by the manufacturer.

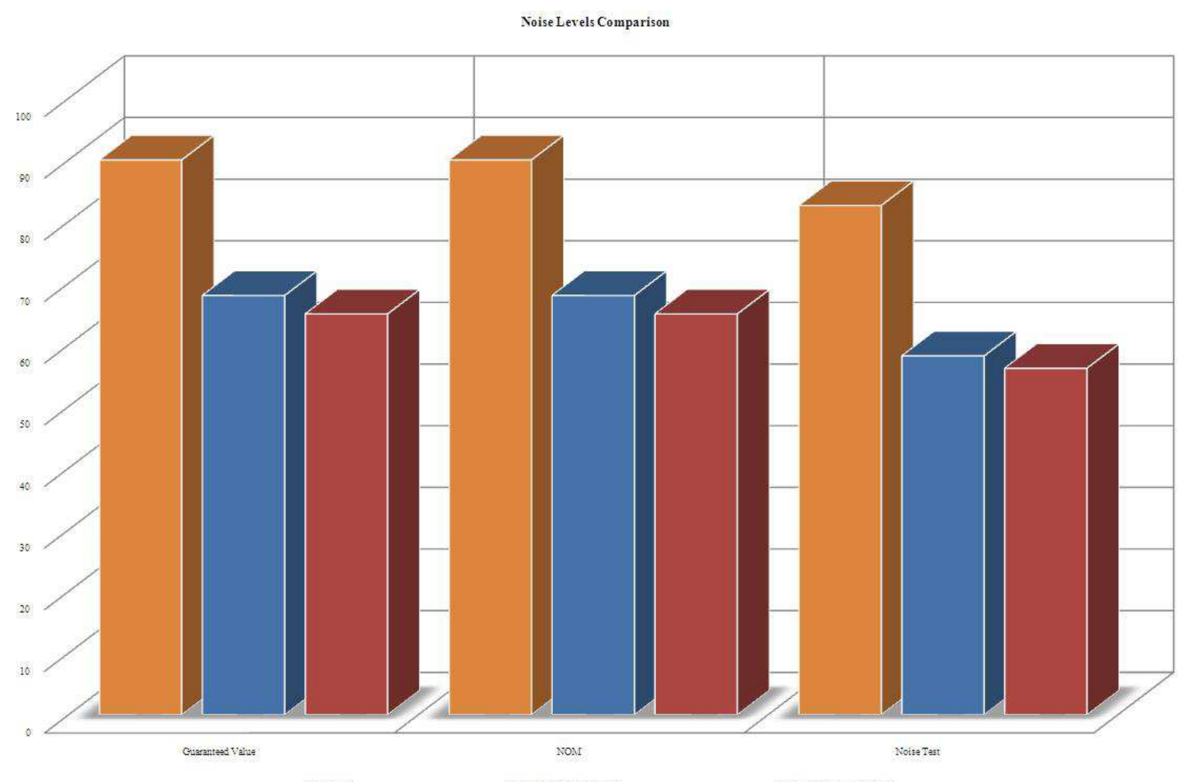

Fig. 15. Comparison of the results obtained during the tests with regard to national and guaranteed values by the manufacturer.

4. Reference model

The reference model based on acceptance test results were generated from the diagnosis develops to the power plants during performance test at the end of the commissioning procedure. This model will be used as a reference basis for the evaluation averages rates that the unit must handle during the history of operation.

In figure 16 is show behavior tendency in terms of average net capacity, developed from the calculated values during the performance test for each one of the fourteen power plants. That is behavior and variation rates that must be have any unit during history operation to maintain it is energetic efficiency.

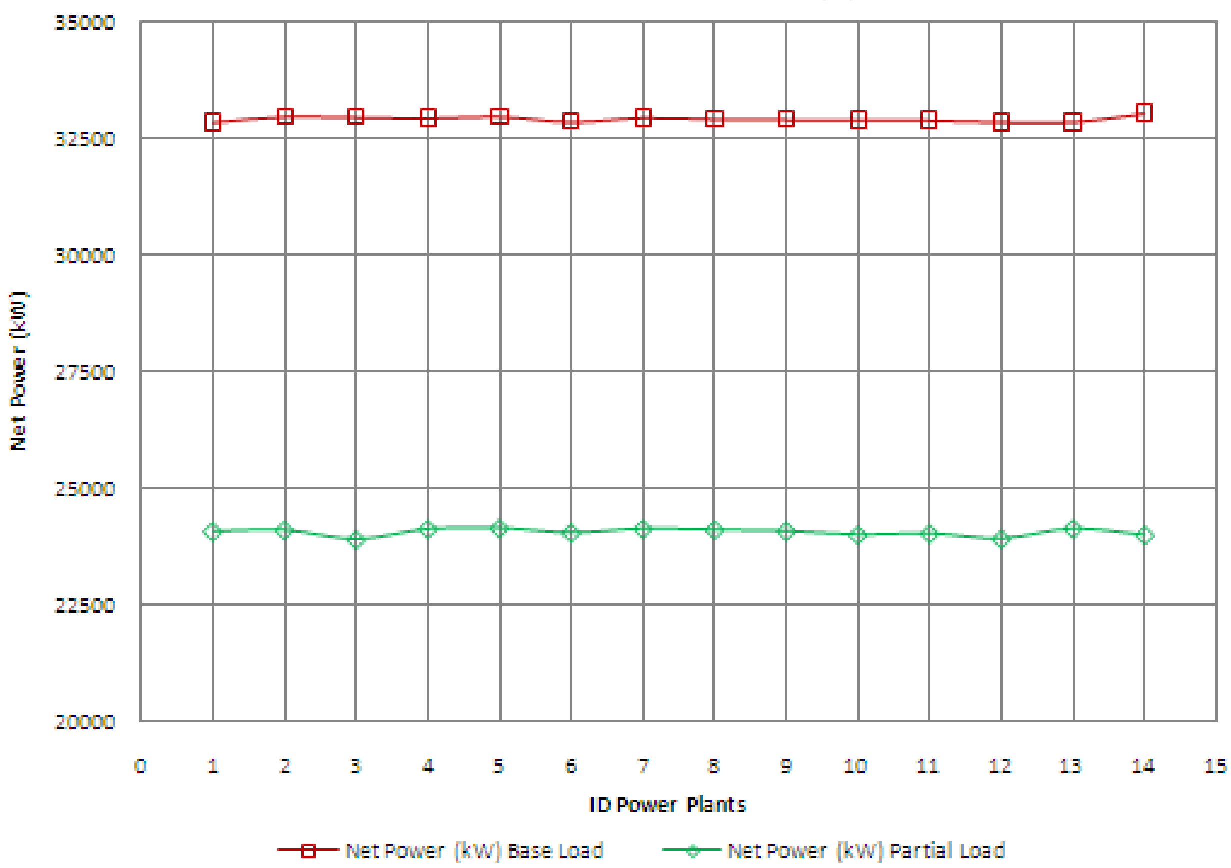

Fig. 16. Reference model of the variation rate in term of average net capacity for a power plant unit at base load or partial load (75 percent).

Furthermore is shown the performance of the unit in terms of emissions to determinate the grade of air pollution exhaust for the power plants. This reference model also was developing from the calculated values during the performance test for each one of the fourteen power plants. It is show in Figure 17.

As a final result of the reference model developed its obtains a Mathematical expressions that consider the average net capacity of the unit based on the emissions levels of the power plant as it show in equation 15:

$$P_{NET} = \alpha NOx^4 - \beta NOx^3 + \phi NOx^2 - \theta NOx + \omega \quad (15)$$

Where: α, β, ϕ, θ and ω are real constans values determined from data colection.

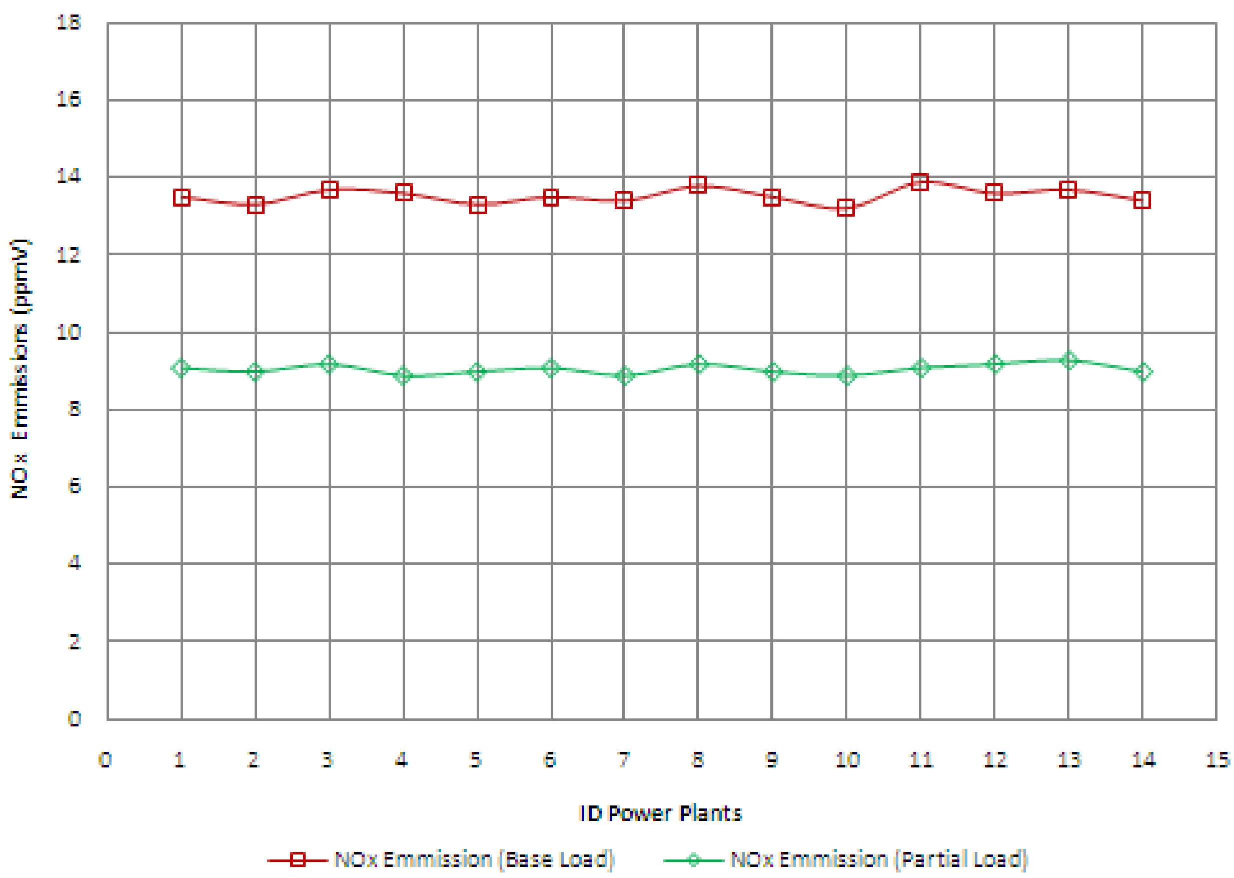

Fig. 17. Reference model of the variation rate in term of emissions for a power plant unit at base load or partial load (75 percent).

5. Conclusions

The goal of this work is to present the fundamentals for determining, through evaluation, a reference model for average net capacity and unit heat consumption as well as pollutant emissions level; furthermore the noise level in fourteen turbo gas power plants.

The model will serve as a reference in terms of Net Power and NOx emissions in the net effects of air quality due to this means of power generation. It will be possible to evaluate, during life history of the unit, the impact through the time due to natural degradation of equipment on the environment. This will be presented as a lower efficiency of the system and higher emissions and noise probably.

The noise levels have been determined for normal operation of unit to establish allowable limits to assure population's health and in the surroundings and personnel. Similarly, the NOx emissions and average net capacity model of reference will be a tool for comparison purposes in future operation.

On the other hand, as a main result of this analysis, it was verified that the unit observes all national and international regulations as well as all requirements previously established between costumer and manufacturer.

Finally, as a result of this study, it is guaranteed to the costumer that this plant will operate correctly satisfying technical requirements, according to unit design and local needs of generation in terms of efficiency and emissions.

6. Acknowledgment

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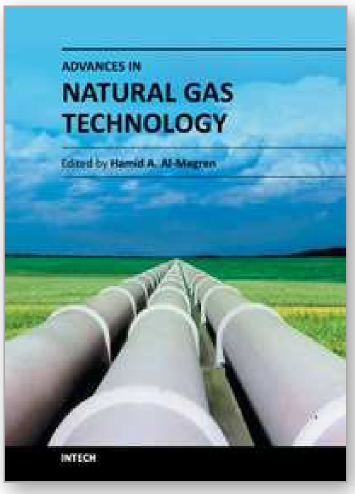

Advances in Natural Gas Technology

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Natural gas is a vital component of the world's supply of energy and an important source of many bulk chemicals and speciality chemicals. It is one of the cleanest, safest, and most useful of all energy sources, and helps to meet the world's rising demand for cleaner energy into the future. However, exploring, producing and bringing gas to the user or converting gas into desired chemicals is a systematical engineering project, and every step requires thorough understanding of gas and the surrounding environment. Any advances in the process link could make a step change in gas industry. There have been increasing efforts in gas industry in recent years. With state-of-the-art contributions by leading experts in the field, this book addressed the technology advances in natural gas industry.