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MODELING AND SIMULATION OF THERMOELECTRIC PLANT OF COMBINED CYCLES AND ITS ENVIRONMENTAL IMPACT

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ABSTRACT

The impact any power plant has upon the environment must be minimized as much as possible. Due to its high efficiency, low emission levels and low cooling requirements, combined cycle plants are considered to be environmentally friendly. This study evaluates the effect of operational conditions on pollutants (CO, CO_2, SO_x, NO_x) emissions levels, waste-heat and wastewater of a combined-cycle natural gas and steam power plant. The HYSYS process simulation was used for modelling and simulation. The study clearly shows that the absolute quantity of pollutants emitted is high. Also, it was possible to verify that the unit operate in the condition of minimal emissions regarding the maximum possible, and thus a reduction or elimination of such pollutants is not possible.

Keywords: thermoelectric, natural gas, environmental impact, combined-cycle, HYSYS.

NOMENCLATURE

R stoichiometric fuel-air ratio
T temperature, ºC

Subscripts

x numbers of oxygen atoms

INTRODUCTION

The thermoelectric plants that use combined cycles integrate two thermal cycles: the gas turbine cycle and the steam turbine cycle, such that the surplus thermal energy from the gas turbine be employed to vaporize water and generate high pressure steam, which drives the turbine of the steam cycle. Figure 1 shows a simplified scheme of a thermoelectric plant of combined cycles.

This process has high efficiency and low level of emission of pollutants, when compared to thermoelectric plants that use fuel oil or coal as fuel. Nevertheless, it is important (and fundamental) to say that the emissions and the water consumption in the cooling towers of the steam cycle must be carefully evaluated, considering the minimization of the process environmental impact, without losing its technical-economical feasibility.

From the results herein shown, it is possible to evaluate the effects of operational conditions in the energy generation and the corresponding environmental impact. The developed model allows the evaluation of the effect of several variables on the whole process.

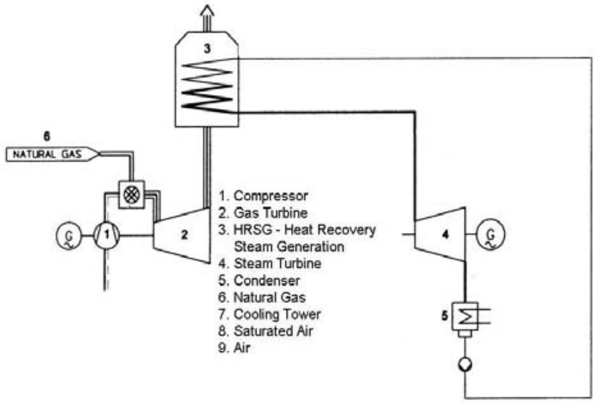

Figure 1. Simplified scheme of a thermoelectric plant.

THE THERMOELECTRIC PLANT

A thermoelectric plant with combined cycles, which uses natural gas as fuel, consists of a natural gas cycle and a steam cycle. In these plants, natural gas is burned in a combustion chamber, followed by an expansion of the exit flue gas in a gas turbine, which generates electrical energy in a turbo-generator. The hot effluent of the gas turbine generates steam in the steam-generator of the steam cycle, which expands in the steam turbine and generates additional electrical energy (Kehlhofer et al., 1999).

Electrical energy production is achieved basically by integrating the production of the natural gas cycle with the production of the steam cycle, excluding the necessary energy to compress the combustion air up to the operating pressure of the gas turbine and to recompress the boiler feed water condensate in the steam cycle.

It is possible to identify the first source of environmental impact as the combustion gases emitted by the plant gas cycle. There is thermal pollution, due to the high temperature of the gases released to the atmosphere, and also chemical pollution from these gases. It is possible to characterize the following pollutants: hydrocarbons and CO from the incomplete burning of the fuel (natural gas), SO_x (SO_2 e SO_3) generated by burning sulphur contaminants (H_2S and mercaptans) presents in the natural gas and NO_x (NO and NO_2), generated by the nitrogen from air oxygenation reaction at high temperature.

Also, CO_2, which is of unavoidable generation in the combustion process, is characterized as pollutant, being the main promoter of the "global warming effect". The main combustion products of natural burning are CO_2 and H_2O, in stoichiometric quantities in relation to the gas being burned. Hereafter shown as tons per hour of yielded CO_2, even though its concentration in the exhaust gases is not dangerous.

Another type of environmental impact is the water consumption in the cooling towers, responsible by the condensation of low-pressure steam in the steam cycle. The water consumption of a thermoelectric plant can be of the order of that of a small city, depending on its capacity. The thermoelectric plants are usually located nearby the cities, so both exploit the same water resource. It is a kind of environmental impact since the plant is using potable water, which will be release in the atmosphere as vapour, and that will not necessarily be recovered in the same place.

In the environmental impact evaluation there exist a necessary comprehension of all aspects involved in the energy generation by thermoelectric plants, including its location.

From the process point of view, the efficiency of useful chemical energy of natural gas converted to electric energy can be evaluated as function of the following variables: i) the air-natural gas molar ratio to be used in the process, and ii) the flue gas temperature in the turbine, constrained by its mechanical and technical reasons. The latter is the main constraint and imposes a loss of efficiency to the process, since it is always active in the system optimisation. So, it is necessary to use a larger excess air quantity than the effectively necessary for complete gas burning. This fact is important from the point of view of process effect in the environment, but do not represent the real and absolute environmental impact, since the use of more oxygen is accomplished by an increasing in the nitrogen quantity. If only flue gas composition analysis is considered, even the flue gas CO_2 content is very small regarding the nitrogen and oxygen content of the exhaust gases.

It is important to point out here that, the low level content does not decrease the whole environmental impact. It could be somewhat more interesting to have one ton of CO_2 per hour diluted to ppm than the same CO_2 quantity with 90% purity level: but one ton of CO_2 per hour still being one ton of CO_2 per hour.

The simulation model developed in the HYSYS simulator integrates all concepts and considerations above explained and allows evaluating the effect of each variable on the overall process. The process flow sheet drawing in the HYSYS simulator is show in Fig. 2.

HYSYS

HYSYS is a professional simulation software, with tools that are applied to many chemical engineering process. Other softwares with similar capabilities, e.g. PRO II and CHEMCAD, could be used in the simulation, with variable degree of difficulty but giving the same solutions.

It is interesting to observe that HYSYS is a software package that can simulate various types of processes, but does not have the specific function to simulate and evaluate thermoelectric plants, based on natural gas or other fuels.

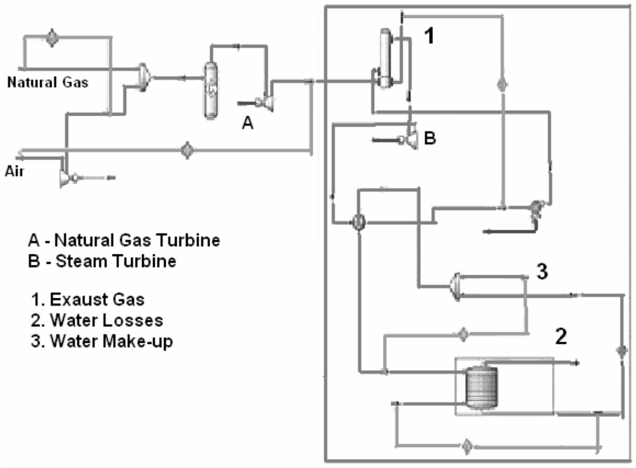

Figure 2. General scheme of a combined-cycle gas steam turbine thermoelectric plant.

METHODOLOGY

All simulations done in this work were based on 1.2 MMm^3/d of Bolivian natural gas flowrate, whose composition is show in Tab. 1.

The chemical reactions in the natural gas combustion process, whose mechanisms were not considered here, are as follows:

1.	$CH_4 + O_2$	$CO + 2\ H_2O$
2.	$C_2H_6 + 1.5\ O_2$	$2\ CO + 3\ H_2O$
3.	$C_3H_8 + 3.5\ O_2$	$3\ CO + 4\ H_2O$
4.	$i\text{-}C_4H_{10} + 4.5\ O_2$	$4\ CO + 5\ H_2O$
5.	$n\text{-}C_4H_{10} + 4.5\ O_2$	$4\ CO + 5\ H_2O$
6.	$i\text{-}C_5H_{12} + 5.5\ O_2$	$5\ CO + 6\ H_2O$
7.	$n\text{-}C_5H_{12} + 5.5\ O_2$	$5\ CO + 6\ H_2O$
8.	$CO + ½\ O_2$	CO_2
9.	$H_2S + 1.5\ O_2$	$SO_2 + H_2O$
10.	$SO_2 + ½\ O_2$	SO_3
11.	$N_2 + O_2$	$2\ NO$
12.	$NO + ½\ O_2$	NO_2

Table 1. Natural gas composition (Bolivian).

Components	Volumetric fraction
Nitrogen	0.01420
Carbon Dioxide	0.00080
Methane	0.91800
Ethane	0.05580
Propane	0.00970
i-Butane	0.00030
n-Butane	0.00020
i-Pentane	0.00050
n-Pentane	0.00050
H_2S	0.00008

From the thermodynamics of chemical reactions equilibrium, the equilibrium state of a system at constant temperature and pressure is that where their total Gibbs free energy is minimal (Santos, 2000). This criterion was used to obtain the equilibrium composition in the combustion chamber, or the minimization of the total Gibbs free energy with respect to the system composition.

All other aspects shown in the flow sheet are elementary, and do not require further detailing regarding the methodology and calculations.

The plant show in the HYSYS scheme, although does not represent the reality of their mechanical construction, it is of high fidelity regarding the engineering aspects and concerns.

RESULTS

The design parameters are: (i) the chimney temperature; (ii) the equipment pressure drops; (iii) the water and ambient air temperatures, and (iv) the turbines efficiencies, taken from literature experimental data. The water losses in the cooling towers were considered to be at the water air saturation concentration.

The simulated data are shown in Tabs. 1 and 2, and agree with the expected results of the process, demonstrating that the parameters used in the process modelling is close to the real ones.

The first process variable to be evaluated is the temperature. Whether in the reactor outlet (combustion chamber) or in the turbine outlet of the combined cycle this variable is a function of assumed stoichiometric relation for the natural gas and air flow rates. For practical applications, it is necessary that this temperature does not exceed a certain limit to ensure the mechanical viability of the turbine.

Figure 3 shows the temperature profile at the turbine inlet. This temperature must be approximately 1200°C, and this condition implies a stoichiometric fuel-air ratio (R) about 2.8. This value is the operational ratio, which will define all other characteristics related to the process.

Table 2. Energy production.

Energy	MW
Energy consumption	**140.7**
Air compression	139.6
Water pump	1.1
Energy production	**361.3**
Gas expansion	270.4
Steam expansion	90.9
Net energy production	**220.6**
Gas cycle	130.8
Water cycle	89.8

Table 3. Process characteristics.

Efficiency - Total	**0.510**
Efficiency - Water cycle	0.182
Efficiency - Gas cycle	0.328

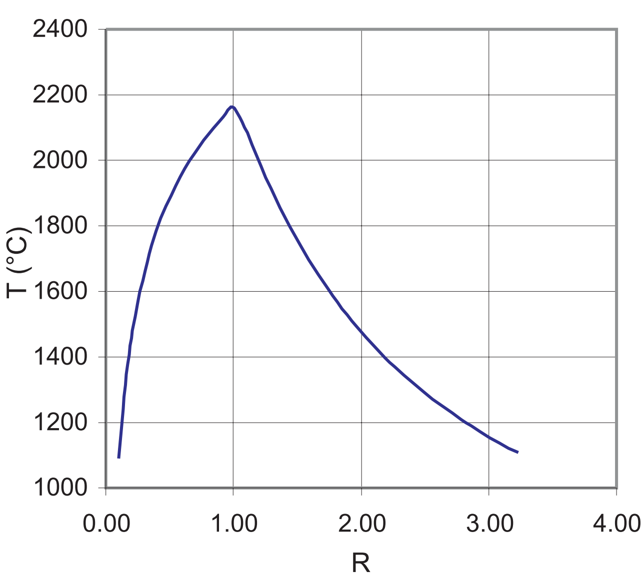

Figure 3. Temperature profile at turbine inlet.

The conditions regarding the chemical reactions can also be evaluated. It is interesting to verify the behaviour of pure air in the reaction conditions, since a similar behaviour is expected during normal operation.

As a general rule, the other environmental impacts promoted by exhaustion in the proposed conditions can be observed (NO_x and CO formation), based on equilibrium reactions.

In Figs. 5 to 7 it is possible to observe that all compositions are attenuated and small. But the absolute values are not so small, due the plant capacity, which produces a very high amount of exhausting gases, as show in Fig. 8.

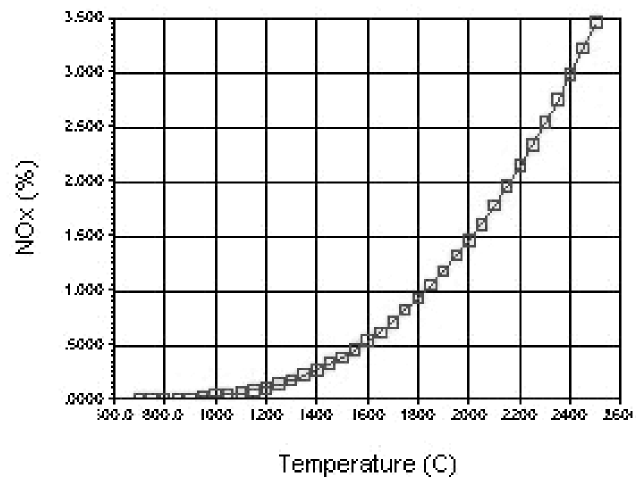

Figure 4. NO_x formation with temperature.

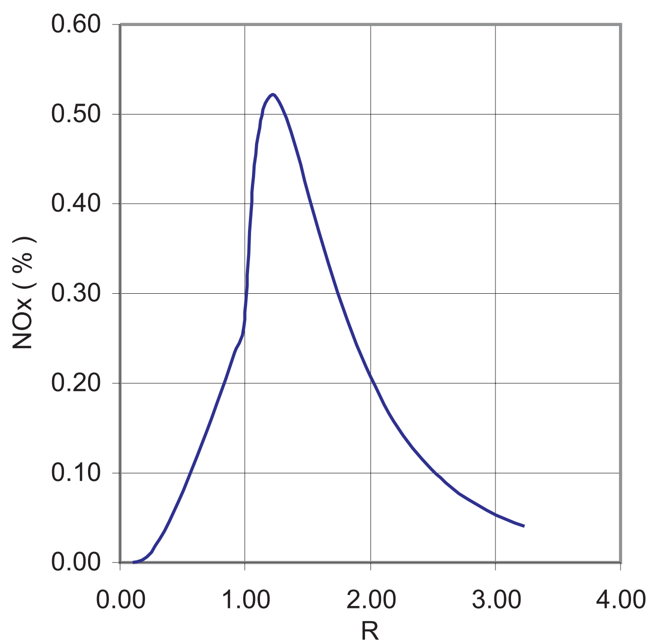

Figure 5. NO_x formation with R.

In a direct way, the absolute amounts of pollutants generated by the plant in study are shown in Tab. 4.

Table 4. Pollutants flowrate

Pollutants	Molar flow rate (kgmol/h)	Mass flow rate (kg/h)
CO	0.0078	0.219
CO_2	2172	95600
NO_x	57	1733

As can be seen in Tab. 4, 1.7 tons/h of NO_x are emitted to produce 267 MWh of electrical energy.

Other important data regards water consumption, 288.5 m^3/d, equivalent to the average water consumption of 300 families.

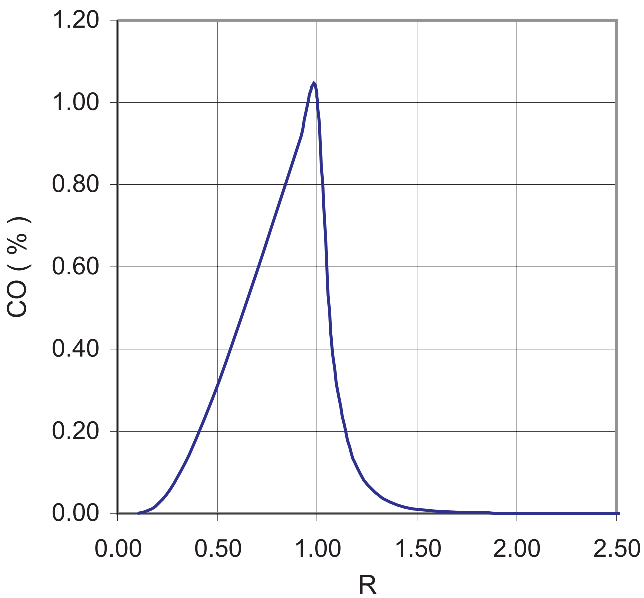

Figure 6. CO formation with R.

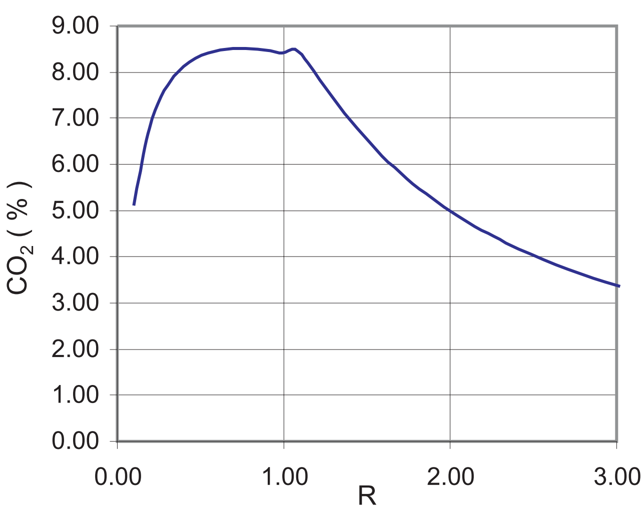

Figure 7. CO_2 formation with R.

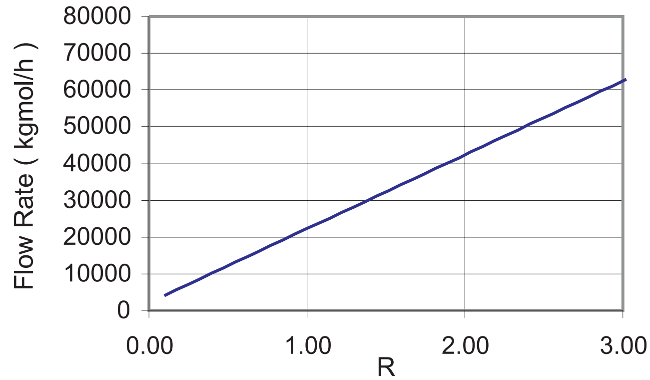

Figure 8. Molar flow rate of exhausting gases.

CONCLUSIONS

The study clearly shows that the absolute amount of pollutants emitted is high. Also it was possible to verify that the unit operates in the condition of minimal emissions regarding the maximal possible, and thus a reduction or elimination of such pollutants is not achievable.

It can be observed from this study that the ideal condition for energy productivity is to operate with a fuel-air ratio as the stoichiometric one. The first constraint to this ideal is the mechanical conditions of the turbine, which cannot operate at the corresponding combustion flue gas exit temperature. So, a stoichiometric ratio in the range of 2.7-2.9 is used, and these conditions make the process viable (turbine viability) and minimize pollutants production (CO and NO_x). These operational conditions are the optimal considering environmental concerns. The CO_2, being a product, is maximized in the process, so there is no need to search for methodologies to minimize their production, but there is for technologies for their capture and uses parallel to the process.

The operational conditions are optimum regarding the environmental impact, but the total emissions are not ideal, that is: zero NO_x production mainly. Its production is 1.4 (ton/h)/(MMm^3/d_gas), nevertheless the small observed concentration.

This type of problem must not be studied and analysed from the point of view of production or environmental protection. The electrical energy production is necessary and fundamental for a society. From the remaining options, some of them do not guarantee a large amount of energy in a broad and continuous way, and depend on nature behaviour whereas others yield much more pollutants than the thermoelectric of combined cycles.

In countries such as Brazil, where natural gas is available, the utilization of this resource in thermoelectric plants is of interest. This does not mean that the plant is not pollutant; the process pollutes, sometimes in large quantities and with considerable toxicity, even in small concentrations. Thus, it is necessary to establish a program that determines the appropriate distribution and location of thermoelectric plants, being interesting the research for new technologies in the search for better use and less environmental impact.

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