INFLUENCE OF AMBIENT TEMPERATURE IN COMBINED CYCLE POWER PLANT PERFORMANCE

Felipe Raúl Ponce Arrieta
Thermal Systems Study Group (NEST), Federal University of Itajubá (UNIFEI), Av. BPS 1303 Caixa Postal 50, Itajubá, MG, Brasil, CEP 37500-903, Tel-Fax: +55 35 3629 1355
e-mail:fponce@unifei.edu.br

Electo Eduardo Silva Lora
Thermal Systems Study Group (NEST), Federal University of Itajubá (UNIFEI), Av. BPS 1303 Caixa Postal 50, Itajubá, MG, Brasil, CEP 37500-903, Tel: +55 35 3629 1321, Fax: +55 35 3629 1355
e-mail: electo@iem.efei.br

Abstract. *Thermal power plants have become an important issue as part of energy supply systems, mainly because of the need of diversified power generation systems and the availability of natural gas, the main fuel used in this type of energy generating system. With the implementation of the Priority Plan of Thermal Power Plants in the Brazilian scenario, dozens of units will be installed which will make it possible to transform the Brazilian Electric System, today mainly based in hydraulic principles, into a hydro-thermal system. The operation of a combined cycle thermal power plant is influenced by the conditions that are present at the place where it is installed, mainly ambient temperature, atmospheric pressure and the air relative humidity. Those parameters affect the generated electric power and the Heat Rate during the operation. Among these variables, the ambient temperature causes the greatest performance variation during the operation. That is the reason why the influence of this variable on this type of generating unit is studied. The plant selected for this study has a multiple shafts configuration and is composed of two Siemens-Westinghouse 501F gas turbines, coupled to three level pressure HRSGs and re-heating with supplementary firing and a steam turbine. The most relevant results obtained from a thermodynamic simulation, in which the Gate Cycle Software version 5.40.0.r was used, are the curves of generated power, as well as, Heat Rate and thermal efficiency as a function of ambient temperature and the supplementary firing after burning temperature.*

Keywords*. Electric power generation, operation, thermodynamic analysis, efficiency, Heat Rate.*

1. Introduction

Thermal power plants began to gain strength in the country after the need of diversifying the generating park and the availability of natural gas, which is the main kind of fuel used by this type of generating unit. The implementation of the Priority Thermoelectric Program will result in the installation of several thermal power plants. This will make the Brazilian Electric System become hydrothermal rather than predominantly hydrological.

It is important to highlight the fact that the behavior and he operation of thermal power plants is considerably more complex than the operation of hydroelectric plants because of the use of working fluids at high temperature and pressure and the consequent difficult operational conditions of the tubes metal, heating surfaces, the turbine combustion chamber, casing, headings, etc. In addition, one must also consider the influence of metals corrosion and erosion caused by different elements, the need of complex automatic control systems, the need to implement system and equipment for pollution control, and the constant effort for maintaining the operation high efficiency and reliability, etc.

Currently, the use of natural gas for thermoelectric generation considering its cost is justified, in most of the cases, at high efficiency installations, which are typical of combined cycle thermal power plants. In this type of generating unit, the operation problems pointed out in the above paragraph manifest themselves in a relevant way, and they are aggravated as a consequence of the presence and interconnection of the main components: gas turbine, HRSG and steam turbine. It is important to highlight that besides these operational problems, those units, designed at ISO conditions (15 °C of ambient temperature, 101,32 kPa of atmospheric pressure and 0,6 of air relative humidity) are extremely sensitive to changes in ambient conditions. The main reason for this sensitivity is the influence of these parameters on off-design gas turbine operation (ambient temperature, atmospheric pressure, relative humidity are different from ISO conditions), where an average of $^{2}/_{3}$ of the plant's total power is generated. In this sense, as a general rule, it is possible to say that combined cycle thermal plants with similar configurations present similar off-design behavioral trends, although different capacities have been projected. (Kehlhofer, et al., 1999).

While the air temperature increases in relation to the project temperature, the power generated by the plant decreases. This is explained by the considerable influence that this parameter has on the power generated by the gas turbine.

According to Kehlhofer, et al. (1999) the gas turbine is designed to operate with a constant air volume in the compressor. When the ambient air temperature increases, its specific mass is reduced. In order to ensure the same air volumetric flow, the mass flow is reduced, causing the power of the gas turbine and the amount of heat generated in the HRSG to fall. The influence of the atmospheric pressure is related to the air density variation. For low pressures, that is, high altitudes in relation to the sea level, the air density is decreases. Disregarding the pressure losses in the gas turbine inlet and outlet ducts, and considering that the efficiency of the steam cycle does not change (facts that happen in a real context), the combined cycle plant presents a behavior that is similar to what was previously explained for ambient temperature. It is important to highlight that the effect of the ambient pressure on the performance must be considered, mainly during the project phase, for once the plant is installed, the variations of this variable are neglected. While the air relative humidity increases, the power generated by the combined cycle plants also increases, considering the other parameters to be constant. In this case, the gas turbine efficiency is slightly reduced, as well as its power. However, the temperature of the gas turbine exhaust gases rises, and therefore the power generated by the steam cycle is increased. The final result depends on which of the factors described above is predominant, but in both cases, the total power variation is very small. Plants presenting cooling towers deserve special attention. In these plants, the air relative humidity is directly related to the level of vacuum in the condenser, and consequently to the temperature of the steam turbine exhaust steam. In these cases, a lower air relative humidity results in a greater vacuum and higher efficiency.

The analysis that was presented allows the supposition that out of these three variables, the ambient temperature has greater influence on the off- design operation of a combined cycle plant. This way, the main goal of this study is to evaluate the influence of this variable on the operation of this type of installation. In order to carry out this study, the values of the other variables were keep constant, for example, atmospheric pressure, air relative humidity, electric energy frequency, power factor, fuel characteristics and its quality, etc.

2. Assumptions

This item describes the suppositions adopted to evaluate the influence of the ambient temperature on the operation. The simplified thermal scheme of the installation selected for the analysis is shown in Figure 1.

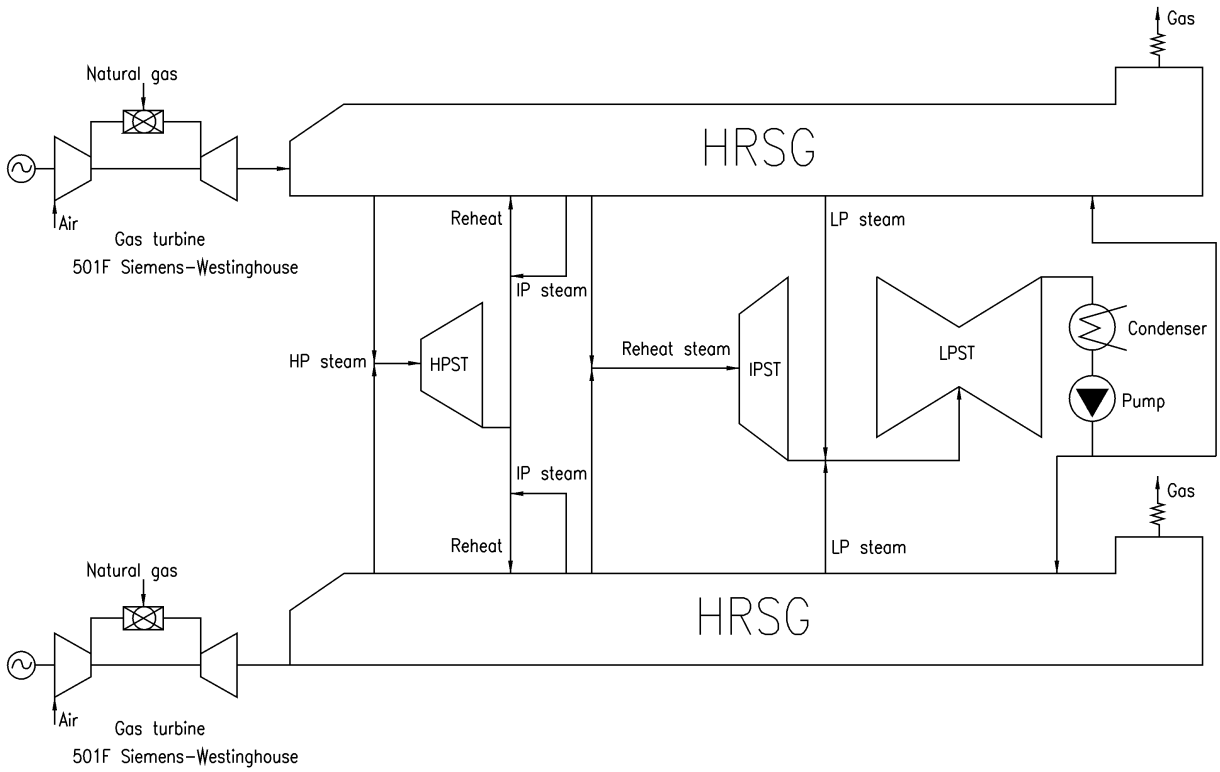

Figure 1 – Combined cycle plant simplified thermal scheme

The thermal scheme main characteristics are:

- Two Siemens-Westinghouse 501F gas turbines;
- Two HRSGs presenting three pressure levels and fuel supplementary firing. A detailed scheme of the HRSG is displayed in Figure 2. According to this figure fuel supplementary firing takes place after the two final high-pressure superheating stages. The first re-heating stage and the first high-pressure superheating stage are placed after the supplementary firing;
- A high, intermediate and low-pressure steam turbine, and the last one presents divided end flow
- Dearator condenser with a cooling system that has wet towers cooling system;
- Cooling system pumps: The low-pressure pump at the condenser outlet and the high-pressure pump is responsible for elevating the water pressure to high and intermediate levels;
- Natural gas supply: The fuel that will be used by the gas turbines is heated, but the fraction that will be used for the supplementary firing is not.

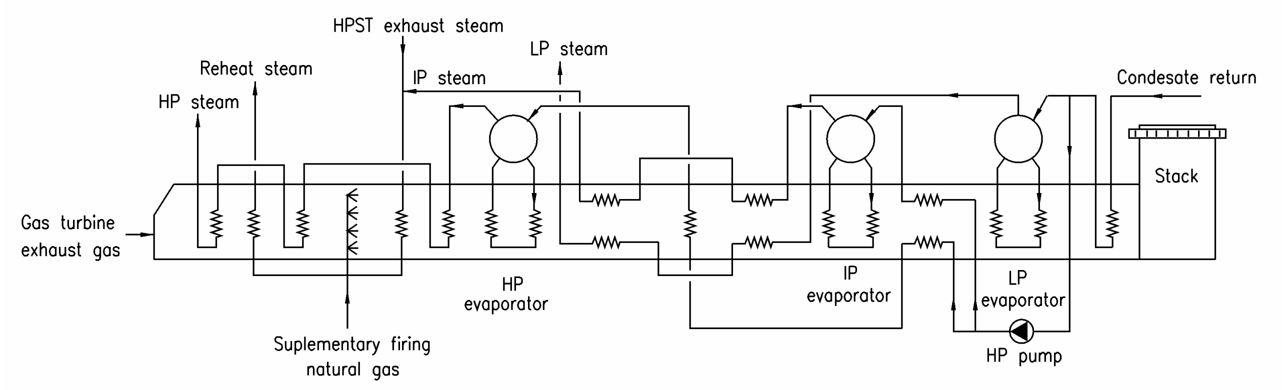

Figure 2. HRSG detailed scheme

Figure 3 illustrates the thermal scheme of a combined cycle drawn by using Gate Cycle version 5.40.0.r. This figure also presents the results of the design point simulation.

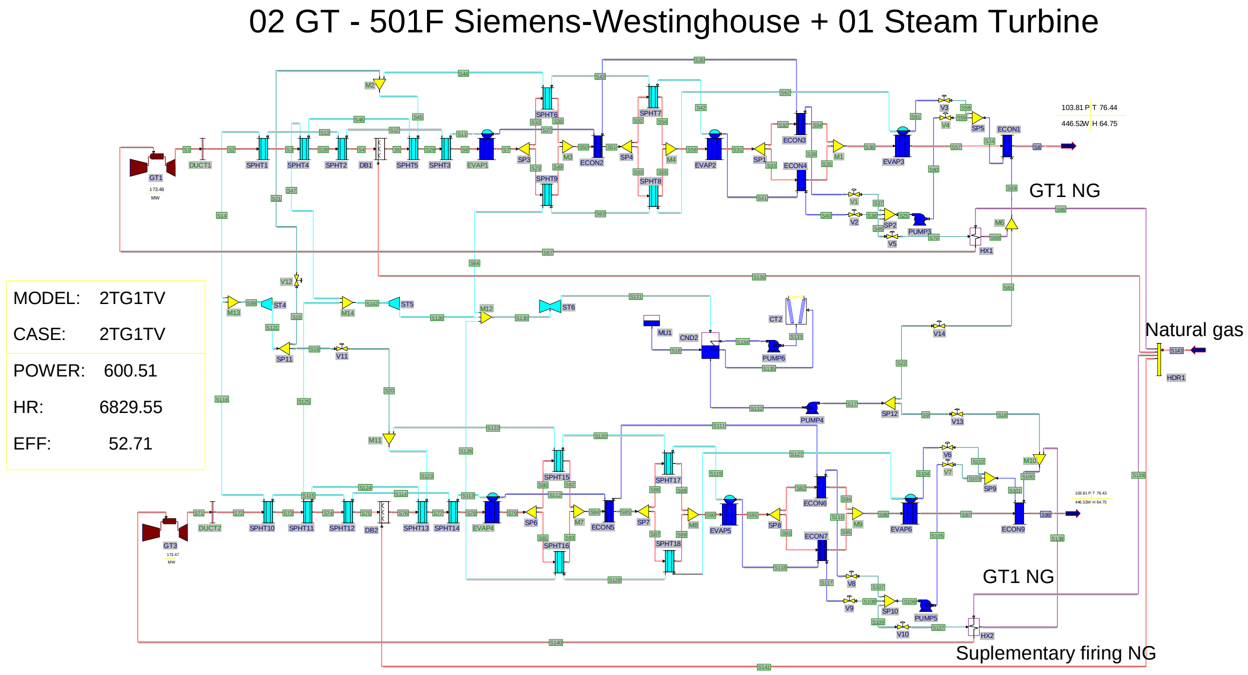

Figure 3. Thermal scheme of a combined cycle plant and the results of the design point simulation

The most important parameters of the installation described above are presented in Table 1 and they refer to parameters used for the thermodynamic simulation at design point.

It is possible to observe that the data shown in Table 1 are divided in four main groups. In the first group, besides the ISO parameters, it is established that the net total electric power generated by the plant at design point is 600 MW. The second group of data defines the fuel used during the simulation, as well as its Low Calorific Value and the supplying conditions. The third group is dedicated to the gas turbine. In this case, the data presented had already been already implemented in the Gate Cycle software when the turbine was selected. The last group is related to the steam cycle and the plant's auxiliary systems. The following values can be observed: steam pressure and temperature for different levels of pressure presented by the HRSG, condenser operating pressure, efficiency of the steam turbine three stages and the imposition of a minimum steam at the low pressure turbine outlet, which is based on technical criteria. The other data that were shown are related to the fuel supplementary firing, the condenser cooling system, the pumps and the BOP power consumption. It is important to highlight that the temperature of the gases after the fuel supplementary firing was limited at 675 °C aiming at avoid the formation of steam in the final section of the economizer tubes.

The final suppositions are related to the calculation of priorities during the simulation. In this sense, water proprieties and steam were determined according to Reynolds (1979), whereas an ideal gas behavior was considered for the gases, and the proprieties were calculated according to Chase Jr. (1998).

Table 1. Main data for the simulation of the combined cycle thermal plant at design point

Parameter, unit	Value
Ambient Temperature, °C	15
Atmospheric pressure, kPa	101.32
Relative humidity	0.60
Net total electric power, MW	600
Fuel:	
Natural gas, PCI, kJ/kg	46515
Supply conditions, MPa/°C	2.758/15
Siemens-Westinghouse 501F gas turbines [(a)]:	
Gross power, MW	174.66
Compression isentropic maximum efficiency	0.90
Combustion efficiency	0.99
Turbine isentropic efficiency	0.9431
Electricity generator efficiency	0.985
Turbine inlet temperature, °C	1382.5
Turbine outlet temperature, °C	608
Cooling air fraction	0.178
Auxiliary power consumption, MW	1.18316
Steam cycle with three levels of pressure and re-heating	
High pressure steam, MPa/°C	15.6/530
Intermediate pressure steam and re-heating, MPa/°C	3.2/530
Low pressure steam, MPa /°C	0.75/305
Condenser operating pressure, kPa	5.06
HRSG [(b)]:	
Additional burning temperature, °C	675
Additional burning efficiency	0.976
Minimal gas exiting temperature, °C	70
Heat transfer coefficient, kJ/s-m^2-K	0.45426
Three-stage steam turbine:	
Net power with additional burning, MW	253.57
High pressure turbine isentropic efficiency	0.8098
Intermediate pressure turbine isentropic efficiency	0.9259
Low pressure turbine isentropic efficiency	0.8867
Minimum quality at the out let of the low pressure steam turbine [(c)]	0.85
Total electromechanical efficiency	0.94464
Condenser:	
Heat exchange area, m^2	30528
Heat transfer global coefficient, kJ/s-m^2-K	2.85
Cooling tower:	
Capacity, kJ/s	421418
Number of fans	10
Fan total power, kW	960.5
BOPs:	
Pump isentropic efficiency	0.75
Total losses referring to the steam turbine power	0.0198

Notes:

a) Source: Gas Turbine World Handbook (1998);

b) The temperature of the gas after the additional burning was limited at 675 °C aiming at avoiding the formation of steam in the final section of the economizer tubes during the off-design operation. The pressure drop of the gas and of the working fluid (water-steam) was not considered;

c) According to Boyce (1999) this value avoids blades erosion within the last stages of the turbine.

3. Methodology

This item intends to explain the criteria used to evaluate the influence of the ambient temperature on the operation and performance of a combined cycle plant and the different stages in which the study was carried out. The particular case of the installation presenting the characteristics shown previously, it is not possible to disregard the effect of the fuel supplementary firing on the plant's performance. By using the fuel supplementary burning in the HRSG, it is possible to mitigate the power loss in the gas turbines caused by a rise in the ambient temperature, affecting the installation's thermal efficiency at the same time. The power loss in the gas turbines is compensated by the supplementary firing, for it is possible to generate more steam in the HRSG, consequently, more power in the steam turbine. This way, aiming at accomplishing this study's goal, a parametric study involving two variables: ambient temperature and gas temperature after supplementary firing, was carried out.

Table 2 shows the values of the variables that were used for the parametric study, that is, for each value of ambient temperature that was considered, the plant's performance was evaluated by using different gas temperature values after the supplementary firing in the HRSG.

Table 2. Parametric study variables and their values.

Variable	Considered values
Ambient temperature, °C	0, 5, 10, 15, 20, 25, 30 and 35
Gas temperature after the supplementary firing, °C	675, 645, 615, 585, 555 and 525

The parametric study was carried out following these stages:

- Stage 1. Selection of the installation's thermal scheme. In this case the choice was a typical scheme of a combined cycle plant for the generation of a net electric power of 600 MW;
- Stage 2. The thermal scheme was drawn using the Gate Cycle software. It includes the components geometric distribution and their interconnection;
- Stage 3. Data input. Data input. It refers to the data input of all the components that form the thermal scheme: gas turbines, HRSGs surfaces, steam turbine, condenser, equipment and auxiliary sub-systems, etc.;
- Stage 4. The scheme and the input data must be fitted to ISO conditions. In this stage, the program was run several times and execution, thermodynamic, physic and geometric data and mathematic parameters errors were analyzed. The main goal of this stage is the make the scheme ready for the off-design simulation;
- Stage 5. Simulation of the off-design operation for each of the different specified ambient temperature values, maintaining the gas temperature after the supplementary firing within project conditions (675 °C);
- Stage 6. Simulation of the off-design operation for each one of the different ambient temperature values, varying the gas temperature after the supplementary firing according to the specified values. As a result of stages 5 and 6, 48 operation variants were attained;
- Stage 7. Verification of results. The analysis of the limit values of different variables was carried out. This analysis aims at avoiding reaching risky values that could jeopardize the operation reliability, for example, steam high temperature at the high-pressure turbine inlet, etc.;
- Stage 8. Elaboration of graphics to analyze the results.
- Stage 9. Result analysis. It will be discuss in the next item.

4. Results analysis

In order to evaluate the performance of a combined cycle plant during off-design operation, because of changes in the ambient temperature and the gas temperature after the supplementary firing, variations in generated power, efficiency and heat rate were analyzed.

The combined cycle plant's net thermal efficiency 'η_{Net}' is given by:

$$\eta_{Net} = \frac{(W_{GT1}[kW] + W_{GT2}[kW] + W_{ST}[kW] - W_{AUXILIARY}[kW])}{\dot{m}_{FUEL}[kg/s] \cdot LHV[kJ/kg]} \cdot 100 \text{ , \%} \tag{1}$$

Where 'W' represents the gross power generated by the gas turbines 'GT1' and 'GT2', the steam turbine 'ST', and the BOP power consumption 'AUXILIARY'. '$\dot{m}$' represents the fuel mass flow consumed in the plant and 'LHV' its Low Heating Value.

The combined cycle plant's net heat rate 'HR_{Net}' is given by:

$$HR_{Net} = \frac{3600.00}{\eta_{Net}[\%]} \text{ , kJ/kW-h} \tag{2}$$

Where the net thermal efficiency 'η_{Net}' is calculated according to equation (1).

Figure 4 shows the variation in the net power generated in the combined cycle plant in relation to the gas temperature after the supplementary firing for the different ambient temperature values that were analyzed. According to this figure, the results of the simulation are:

- It is observed that for any ambient temperature the operational performance tendency is the same: The rise in the temperature of the gas after the supplementary firing increases the power generated in the plant. This behavior is caused by the increase in the power generated in the steam turbine;

- It is also observed that for the gas studied temperature range after the supplementary firing it is possible to generate up to 70 MW more power in the installation;
- The change in the studied parameters has a significant influence on the power that can be generated in the installation. For the maximal ambient temperature and the minimal gas temperature after the supplementary firing, the generated power is 468 MW, whereas for the minimal ambient temperature and the maximal gas temperature after the supplementary firing, the generated power is 642 MW, that is, a variation of 170 MW in the generated power was registered.

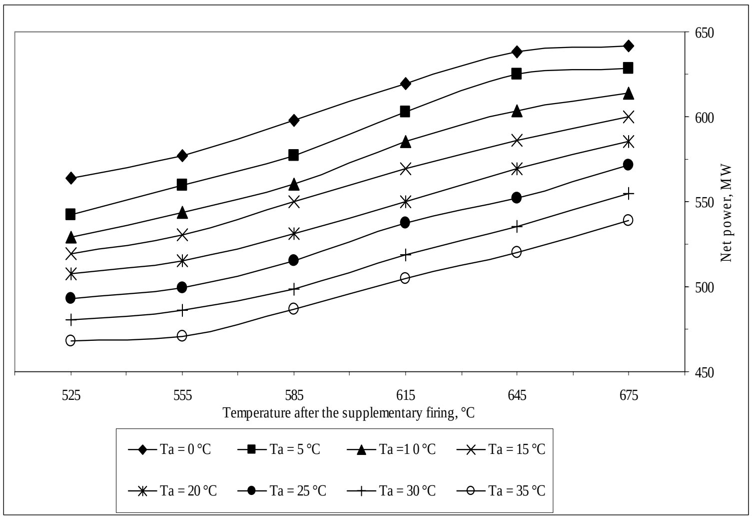

Figure 4. Net electric power generated

Figure 5 illustrates the variation in the net power generated in the gas and steam cycle of the combined cycle plant in relation to the ambient temperature. The dark part of the graphic shows the net power generated in the gas cycle, whereas the gray part shows the net power generated in the steam cycle. The evident result is that the sum of the two net powers generated in both cycles is equivalent to the net power generated by the combined cycle plant. In this graphic, the eight peaks that were observed correspond to the condition of maximal gas temperature after the supplementary firing for each one of the values of ambient temperature that were analyzed, whereas the valleys correspond to the condition of minimal gas temperature after the supplementary firing. The following observations can be made according to this figure:

- The strong influence of ambient temperature produces a fall in the power generated in the gas cycle from 380 MW to 305 MW, that is, 75 MW approximately;
- By using fuel supplementary firing, for the whole range of temperatures after the firing that was analyzed, it is possible to have a power gain in the steam cycle of approximately 77 MW;
- So, it is possible to say that the use of supplementary firing in a combined cycle installation allows a significant compensation for the falls in the power generated in the gas cycles caused by variations in the ambient temperature.

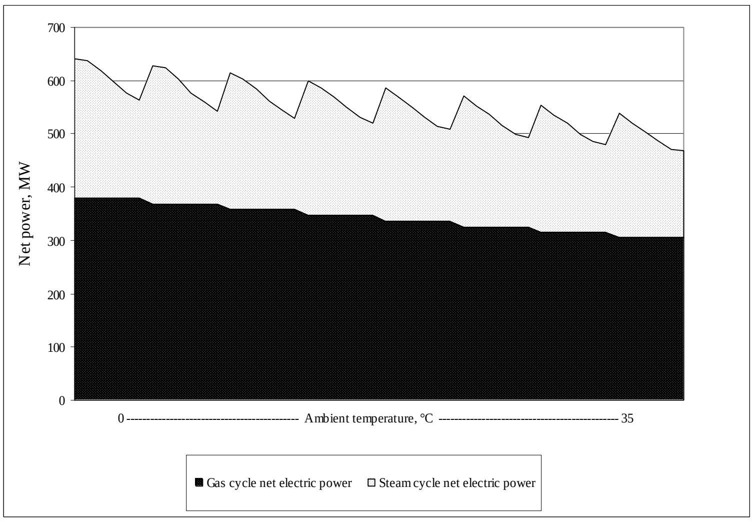

Figure 5. Net electric power generated in the gas and steam cycles

Figure 6 shows the region where the combined cycle plant's thermal efficiency value can be found in relation to the variables considered for this study. According to this figure, the following was observed:

- Regarding ambient temperature, the highest efficiency values are registered when the ambient temperature is lower. This is the result of an increase in the power generated by the gas cycle because of the ambient temperature reduction. For a temperature of 0 °C the efficiency variation lies in a range between 53.5 % and 55.5 %;
- In relation to the temperature of the gas after the supplementary firing, the highest efficiency values were registered when the gas temperature after the supplementary firing is smaller. This behavior takes place due to a reduction in fuel consumption in the HRSG burners in order to achieve a lower gas temperature. Supplementary firing causes, in average, a fall in efficiency of 1.5 percentage points for any of the ambient temperature values that were studied;
- It is possible to say, as a result, that the combined cycle thermal efficiency variation lies within the range of 52 % and 55.4 %, that is, it is 3.4 percentage points approximately.

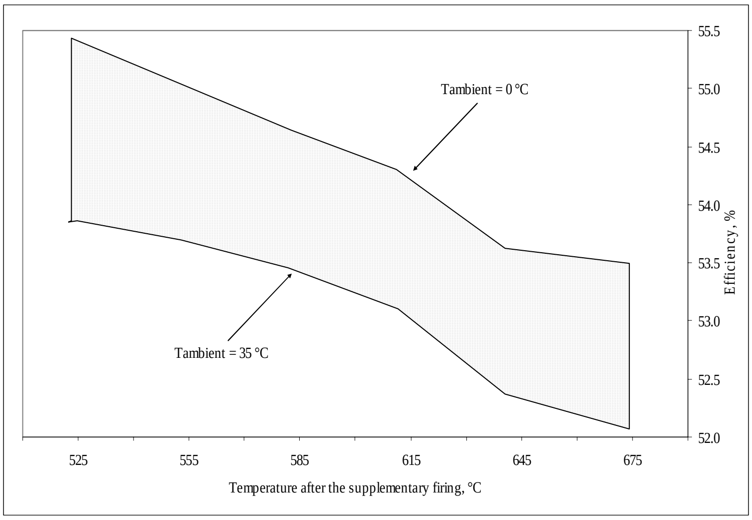

Figure 6. Net efficiency.

Figure 7 shows the results of the parametric study as a function of the analyzed variables , highlighting the effect of supplementary firing. According to this figure it is possible to make the following observations:

- While the ambient temperature rises, the net power generated in the combined cycle thermal plant decreases in spite of the use of the maximal supplementary firing temperature. It was registered that with a gas temperature of 675 °C after the supplementary firing, the net electric power varies in a range from 640 MW to 540 MW when the ambient temperature varies between 0 °C and 35 °C;
- While the ambient temperature rises, the combined cycle thermal plant's heat rate increases (that is, the efficiency decreases), in spite of the use of the minimal supplementary firing temperature. The heat rate value is even greater when the maximal supplementary firing temperature is used.

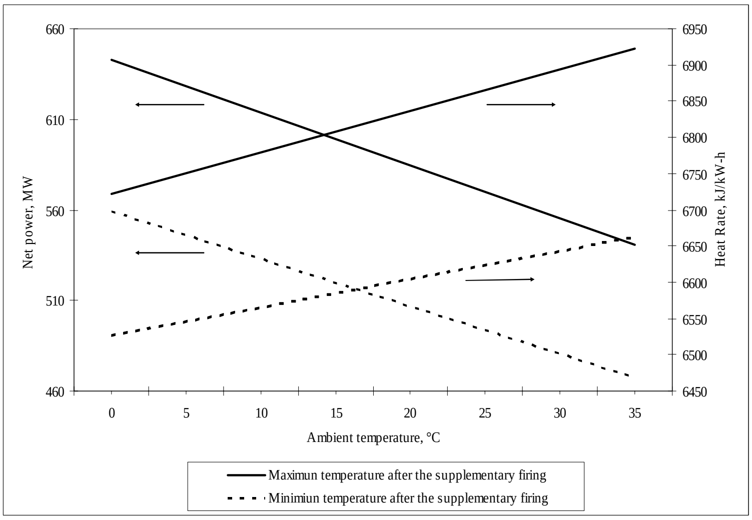

Figure 7. Power and heat rate

5. Conclusions

The parametric studied carried out to evaluate the influence of the ambient temperature on the operation and performance of combined cycle plants allows the following conclusions to be expressed:

- The ambient temperature has a significant influence on this type of generating unit. Within the range of values that was analyzed, a variation in the net power in the gas cycle of approximately 75 MW was registered;
- The ambient temperature and the temperature of the gas after the supplementary firing produce different effects on the combined cycle plant's performance. A drop in the ambient temperature increases the electric power generated in the plants and its efficiency as well, and vice-versa. The rise in the temperature of the gas after the supplementary firing increases the generated electric power but reduces efficiency, and vice-versa. The variation of these two variables led to a variation in the generated net electric power of 170 MW, and a variation in efficiency of 3.4 percentage points;
- The fuel supplementary firing is a technological alternative that can mitigate the power reduction in the gas cycle caused by a rise in the ambient temperature. However, it is evident that this alternative utilization reduces thermal efficiency. This way, the project of combined cycle thermal plants with supplementary firing in HRSGs is restrict to installation where expenses with investment and fuel are lower than the income attained by selling the surplus generated energy. In other words, the use of supplementary firing must be analyzed taking the economic context into account. This way, it is possible to compare its positive effects (mitigation of power reduction due to a rise in ambient temperature and/or the generation of surplus power for the market) with its main negative effect that is the fall in the cycle's efficiency.

Finally, it is important to highlight that the operation of combined cycle thermal plants, is very complex, and that this study is far from establishing definitive criteria about it. In this sense, the researchers of Thermal Systems Study Group will continue carrying out studies in order to find a better understanding of the variables that may have influence on the operation and performance of this type of generating unit. In the future, they will be studied both from a thermodynamic and an economic point of view. Other types of configurations that may become the representatives of new thermal plants installed in Brazil and real cases based on the existing plants will also be studied.

6. Acknowledgements

The authors would like to thank the CNPq (National Council for Scientific and Technological Development) for the financial support granted for this study.

7. References

Boyce, M., 1999, "Performance monitoring of large combined cycle power plants", PWR- Vol. 34, Joint Power Generation Conference, Vol. 2, ASME, pp.183-190.

Chase Jr., M. W., 1998, "NIST-JANAF Thermochemical tables", Fourth edition, American Institute of Physics.

Gas Turbine World Handbook, 1998, Pequot Publishing, Fairfield, CT, USA.

Kehlhofer, R. H.; Warner, J.; Nielsen, H.; Bachmann, R., 1999, "Combined Cycle Gas-Steam Turbine Power Plants", USA, Ed. Pennwell, USA, 288 p.

Reynolds, W. C., 1979, "Thermodynamics properties in SI", Stanford University Department of Mechanical Engineering.

8. Copyright Notice