

POWER AUGMENTATION TECHNOLOGIES FOR GAS TURBINES: A REVIEW AND A STUDY ON THEIR INFLUENCE ON THE PERFORMANCE OF SIMPLE CYCLE POWER PLANTS

César Celis, ccelis@ituc.puc-rio.br
Vinicius Pimenta de Avellar, vavellar@ituc.puc-rio.br
Sandro Barros Ferreira, sandro@ituc.puc-rio.br
Institute of Energy, Pontifícia Universidade Católica do Rio de Janeiro, Rua Marquês de São Vicente 225, RJ 22453-900, Rio de Janeiro, Brazil

Sergio Leal Braga, slbraga@mec.puc-rio.br
Department of Mechanical Engineering, Pontifícia Universidade Católica do Rio de Janeiro, Rua Marquês de São Vicente 225, RJ 22453-900, Rio de Janeiro, Brazil

Abstract. *In simple cycle power plants based on gas turbines, the power output is considerably reduced with the increase in ambient temperature. Many technologies of power augmentation for gas turbines have been proposed along the past few decades, and several systems have already been applied in real plants. Power augmentation techniques are based on the philosophy of increasing the mass flow rate which goes through the gas turbine, which, in turn, increases the gas turbine power output. The increase in the mass flow rate is achieved either by reducing the gas turbine inlet temperature or by direct injection of working fluid. The goal of this paper is to give a comprehensive review of the different technologies of power augmentation available today for gas turbines, as well as to evaluate and to select the best alternative of power augmentation for a specific simple cycle power plant in Brazil. The calculations are carried out using an in-house computer program, called the Power Augmentation Technologies (PAT) model, developed for thermal performance modeling and financial analysis. In order to validate the computational model developed, the authors carried out comparisons between the results obtained with this model and data obtained from literature. Results of a case study, corresponding to a specific simple cycle power plant, show that significant improvements in power output and thermal efficiency can be achieved through the use of all the power augmentation technologies analyzed. In particular, considering the net present value as the main investment economic indicator determining the implementation of a project of this category, the results show that the power augmentation systems based on refrigerating processes and injection of steam in the combustor are the most suitable for this specific simple cycle power plant.*

Keywords*: Power augmentation, simple cycle power plant, thermoeconomics*

1. INTRODUCTION

Simple cycle power plants (SCPP) are electric generating systems which thermal efficiency shows high levels when compared to other commercially available systems. This aspect, in conjunction with particular characteristics such as low capital cost, low emissions, fuel and operation flexibility, high reliability and availability, among others, has made these generating systems suitable for applications to different sites and operating conditions. Due to the fact that simple cycle power plants are based on gas turbines (GT), the power generated from these power plants is considerably reduced with the increase of the ambient temperature. This is due to the fact that the air density decreases as the ambient temperature rises. Because gas turbines are almost constant volume machines at a specified rotating speed, this air density decrease originates a reduction of the mass flow rate going through the gas turbine. The reduction of the mass flow rate, in turn, decreases the power output generated by the power plant. This power output reduction is from 0.5% to 0.9% of the ISO output power for every 1°C rise in the ambient temperature (Ameri *et al*., 2004). The fact that the power output of gas turbine based power plants is reduced during the periods of high ambient temperature, together with the development of a more competitive power generation market, originates a growing interest on the different techniques, or methodologies, of power augmentation for gas turbines. These power augmentation technologies are based on the philosophy of increasing the mass flow rate which goes through the gas turbine, which, in turn, increases the gas turbine power output. As indicated by Boyce (2002), the increase in mass flow rate is achieved either by reducing the gas turbine inlet temperature or by direct injection of working fluid.

There are several technologies available for power augmentation through the reduction of the gas turbine inlet temperature. These methods can be subdivided in evaporative cooling methods (Bhargava and Meher-Homji, 2002, Bhargava *et al*., 2005, Ingistov, 2000, and Kim and Ro, 2000), refrigerated inlet cooling systems (Al-Bortmany, 2002, Alhazmi and Najjar, 2004, and Kakaras *et al*., 2004), thermal energy storage systems (Yokoyama and Ito, 2000), and evaporative cooling of pre-compressed air (Kakaras *et al*., 2004). Evaporative cooling methods are based on the evaporation of water in the intake air of the gas turbine. There are two main types of evaporative coolers: (i) media-based coolers, and (ii) fogging. In both methods, the gas turbine inlet temperature is reduced due to the latent heat of evaporation of the water which is absorbed from the surrounding air. Refrigerated inlet air cooling systems are more effective than evaporative cooling systems, because the formers can reach lower air dry bulb temperature than the evaporative systems. However, the cost of the machinery, and the installation and the operating costs are much higher (Zadpoor and Golshan, 2005). The two main types of refrigerated inlet air cooling systems include: (i) mechanical refrigeration, and absorption cooling, where the heat provided by gas, steam or gas turbine's exhaust is used for cooling the water which acts as refrigerant (Zadpoor and Golshan, 2005). In the thermal energy storage systems, a cold reservoir is built up using the extra power of off-peak hours and then it is utilized during the peak hours to chill the inlet air, increasing, thus, the turbine power output. In the evaporative cooling of pre-compressed air, an electrically driven fan is used for pre-compressing of the inlet air supplied to the compressor of the gas turbine, resulting in a temperature rise of the intake air, which is then cooled by an evaporative cooler.

Usually injection of steam or water in the combustor has been applied for NOx control (Boyce, 2002). However, it also boosts power due to the increased mass flow and higher specific heat of the combustion products going through the turbine (Wang and Chiou, 2004, and Tawney *et al*., 2001). In practical applications, several techniques of power augmentation consisting of injection of compressed air, steam or water have been utilized. These technologies differ from each other, mainly, by both the injected substance and the location where is performed this injection. Normally, the injections are performed into the mid-stages of the compressor and in the discharge section of both the compressor and the combustion chamber. In the interstage water injection systems (Ingistov, 2001, Ingistov, 2002, and Roumeliotis and Mathioudakis, 2005), water is injected into the mid-stages of the compressor to cool the air and to achieve a quasi isothermal compression process. The injection of water within the compressor is expected to reduce the compression specific work mainly by the cooling effect due to the water evaporation, which also performs an on-line washing process (Bagnoli *et al.*, 2004). It is important to mention that water injection between compressor stages can significantly load the blades of this equipment, and droplets can erode compressor blades. At the exit section of the compressor, heated compressed air (Nakhamkin *et al.*, 2000), steam or water can be injected, which consequently could increase not only power, but also turbine efficiency (Boyce, 2002). Finally, it is important to emphasize that the combined use of the above power augmentation techniques must also be investigated, as none of these techniques excludes each other and can be easily used in conjunction. In this sense, Wang and Chiou (2004) and Tawney *et al*. (2001) present works related to the combined use of different technologies of power augmentation currently available. The development and use of a computational model able to simulate existing power plants, either simple cycle or combined cycle, under different power augmentation systems, coupled to an economic analysis, distinguishes this work from the references above mentioned.

The main goal of this paper is to evaluate and to select the best alternative of power augmentation for an existing simple cycle power plant. Thus, next sections show a thermoeconomic analysis of the different possibilities of power augmentation for a specific power plant, i.e., through the use of the different technologies of power augmentation applicable to the plant and combinations of those technologies. The calculations carried out in order to analyze the influence of the use of these different power augmentation systems on the performance of the selected power plant are performed using an in-house computer program, which was developed for performing thermoeconomic evaluations of any simple (SCPP) or combined cycle power plant (CCPP). Details of the PAT model, including the different techniques of power augmentation implemented on it, are shown in the following section. The final part of the paper shows the results of the use of the PAT model to analyze different alternatives of power augmentation for an existing simple cycle power plant in Brazil.

2. THE PAT MODEL

The PAT model is a computer program developed by the authors to evaluate both thermodynamically and economically different alternatives of power augmentation for simple and combined cycle power plants. For the development of the model, two basic aspects were considered: (i) the plant configuration to be analyzed by the model should be as simple as possible, (ii) and the assumptions considered should simplify the thermoeconomic analysis, but, at the same time, should allow representing accurately the operating conditions of actual plants.

Regarding the first consideration, what one intends is that the PAT model is able to simulate a number of power plant configurations under different operating conditions. Thus, currently the model is able to simulate any simple cycle or combined cycle power plant under different power augmentation methods. Details of the plant configuration on which is based the PAT model can be seen in Figure 1. It is also important to highlight that the PAT model is not intended to produce absolute results, in terms of power output and thermal efficiency of the power plant, but to estimate the relative improvements of these parameters, which are obtained through the use of the different technologies of power augmentation currently available within the model.

2.1. Thermodynamic approach

As previously mentioned, the PAT model was developed on the basis of the plant configuration shown in Figure 1. On this plant configuration, which corresponds to a standard one pressure level combined cycle power plant, all the power augmentation technologies studied are added and their influence on the power output and thermal efficiency are analyzed.

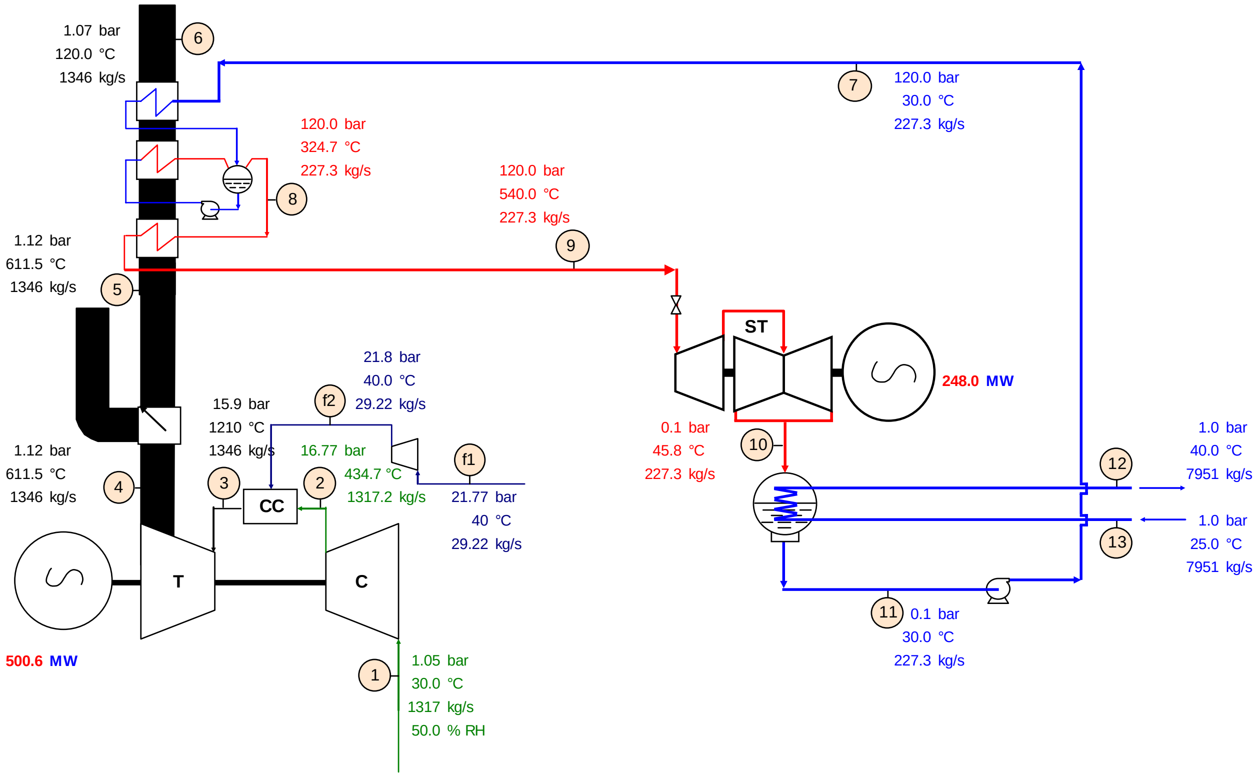

Figure 1. Plant configuration used as basis of the PAT model

The basic plant configuration consists of compressor (C), combustion chamber (CC), turbine (T), heat recovery steam generator (HRSG), steam turbine (ST), condenser and electric generators. Currently, the PAT model allows the analysis of eight different possibilities of power augmentation, as follows: two evaporative cooling methods (media-based cooler and fogging system), two refrigerated inlet cooling systems (mechanical refrigeration and absorption cooling), injection of steam in the combustor, and the other three options correspond to the combined use of the techniques previously mentioned. More details of these power augmentation techniques implemented on the model are shown in the section corresponding to the case study analyzed in this work. Also, it is worthy to highlight that the development of the PAT model continues, mainly, seeking to add other practical methodologies of power augmentation for gas turbine based power plants.

The values of the specific heat, enthalpy, and entropy of air and combustion products are necessary for the analysis of the gas cycle. So, in order to have an efficient tool to calculate these thermodynamic properties, a set of polynomial equations has been utilized. These polynomial equations (McBride *et al.*, 1993), together with their respective set of coefficients, were inserted in the computer model. Validation of the concerned equations is presented by Ferreira (2002). The enthalpy and entropy of both water and steam, which are needed for the thermodynamic analysis of the steam cycle, were computed using the mathematical relations presented by Dechamps (1999).

In order to simplify the analysis, the concept of isentropic efficiency is used to model the compressor, turbine, and steam turbine. The values of these efficiencies are adjusted by the user in order to more accurately model the specific power plant under analysis. The combustion chamber is assumed to be insulated, and pressure losses are modeled considering a pressure drop as a fraction of the inlet pressure. Losses in pressure are also considered in the turbine exhaust, inlet air coolers, and in all the heat exchangers, including the HRSG. Additional energy losses are also included through combustion efficiency, mechanical efficiency, and generator efficiency.

The working fluid passing through the compressor and the turbine is considered as an ideal mixture of air and water vapor, and as an ideal mixture of flue gases and water vapor, respectively. The PAT model considers the air, water vapor, and flue gases as ideal gases. The working fluid of the steam cycle is modeled as a pure substance (water), which means this substance has a homogeneous and invariable chemical composition irrespective of the phase or phases in which it exists. In the cases in which the inlet air temperature of the compressor is decreased by using evaporative cooling methods (media-based cooler and fogging system), the water evaporation process is modeled as an adiabatic saturation process, which considers a cooling system effectiveness, Equation (1), in order to determine the temperature drop of the air stream and the amount of water which is required by the cooling system. In Equation (1), ε represents the cooling system effectiveness, T_{aDB} is the dry bulb temperature (ambient), T_{aWB} is the wet bulb temperature (ambient), and T_{1DB} is the dry bulb temperature at station 1 (Figure 1).

$$\varepsilon = \frac{T_{aDB} - T_{1DB}}{T_{aDB} - T_{aWB}} \tag{1}$$

Refrigerated inlet air cooling systems (mechanical refrigeration and absorption cooling) are modeled as cooling coils through which a refrigerant substance circulates. In the model, the coil exit temperature is adjusted to allow air to reach the desired temperature. Then, using the First Law of Thermodynamics, the cooling load (*Q*) to be removed from the air is estimated. Finally, considering that this cooling load is removed using a typical refrigeration system having a fixed coefficient of performance (*COP*), the power *W* (mechanical refrigeration) or the amount of heat *H* (absorption cooling) need to operate such system is estimated by,

$$W \quad or \quad H = \frac{Q}{COP} \tag{2}$$

The injection of steam in the combustion chamber is modeled following the methodology indicated by Horlock (2003) for the case of "wet" gas turbine plants, i.e., carrying, for convenience, the enthalpy of the steam quantity separately through the analysis, even though it is clear that the steam and gas are fully mixed at all stations downstream the combustion process. In a general sense, the modeling of this power augmentation system involves the determination of the fuel/air ratio, which is obtained from the energy and mass balance in the combustor, considering the amount of steam being injected, and the amount of energy needed to generate the steam to be injected in the combustion chamber. There are a number of other considerations taken into account for in the development of the PAT model, such as the operating pressure and the superheat temperature of the steam cycle, pinch point temperatures, cooling medium inlet temperatures, condensing pressure, and exhaust steam quality of the steam turbine, among others. However, for the sake of brevity, they will not be detailed here.

In order to carry out some kind of validation or verification of the model developed, comparisons of the results obtained from the simulations of both a simple cycle and a combined cycle power plant using the PAT model with data obtained from literature were performed. Thus, Figure 2 and Figure 3 show comparisons between the values of power output and thermal efficiency obtained numerically and those obtained from literature (Bhargava and Meher-Homji, 2002, and Chiang and Wang, 2005) for the cases of a simple cycle and a combined cycle power plant, respectively.

The data which is used as reference for the comparisons with the results obtained using the PAT model corresponds, in the case of the simple cycle power plant, to an industrial gas turbine (GE Frame-7) (Bhargava and Meher-Homji, 2002), and in the case of the combined cycle power plant, to a power plant composed of two 11N2 Alstom gas turbines, two HRSGs, and one steam turbine (Chiang and Wang, 2005). These plant configurations are similar to the basic plant configuration used to develop the PAT model. From Figure 2 and Figure 3, it is possible to see that the results obtained from the PAT model present good agreement with the literature data. This aspect illustrates that the PAT model has an acceptable grade of reliability for performing this type of simulations.

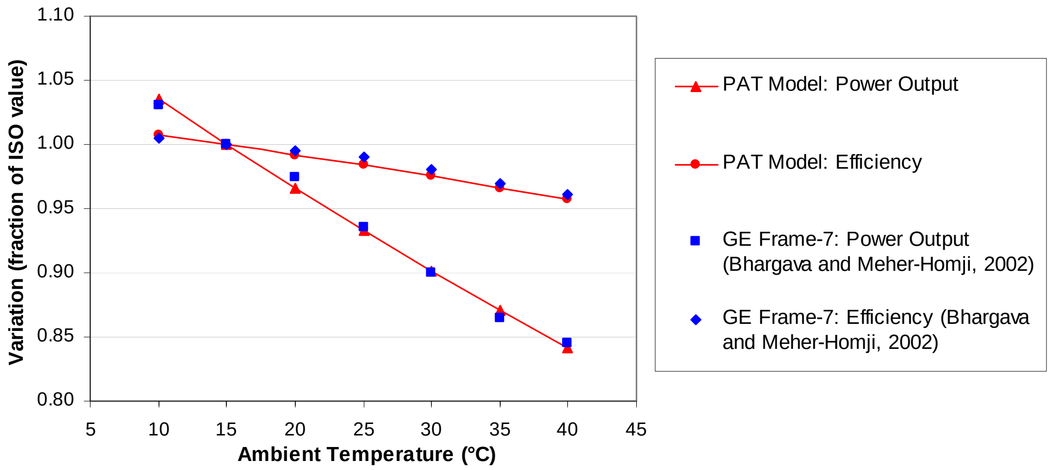

Figure 2. SCPP - Comparison between literature data and results obtained from simulations using the PAT model

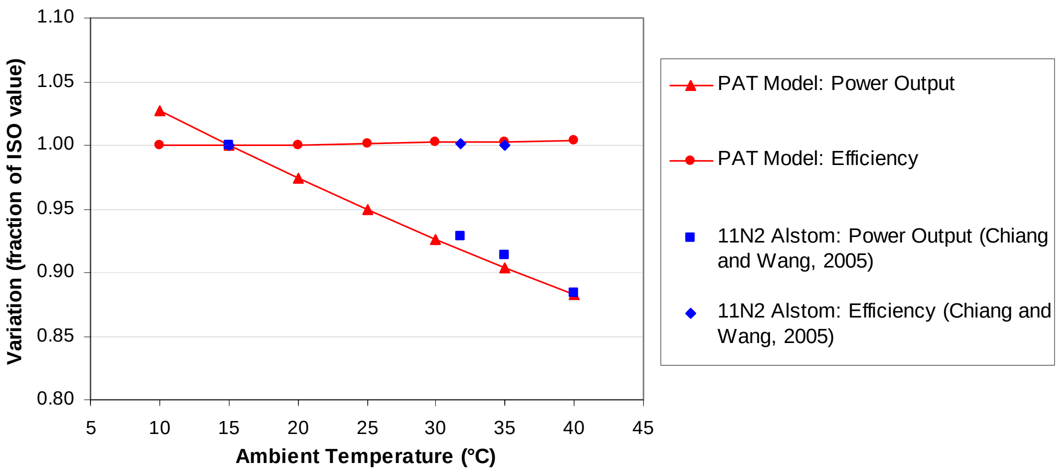

Figure 3. CCPP - Comparison between literature data and results obtained from simulations using the PAT model

2.2. Economic approach

Considering that being economical is one of the most important factors in analyzing the feasibility of any project, in particular those related to the installation and operation of power augmentation systems in gas turbines power plants, the PAT model also includes routines developed exclusively for the evaluation of the economic performance of the investment. In order to assess the economic performance of the different alternatives of power augmentation available on the PAT model, several economic indicators of the investments, including the pay-back period, the internal rate of return (IRR), and the net present value (NPV) are calculated. These calculations are performed based on considerations such as the annual amount of operation hours of the power augmentation system, fuel price, demineralised water price, price of electricity, among others. The results of the thermoeconomic analysis obtained using the PAT model for an existing simple cycle power plant in Brazil are shown in the following case study.

3. CASE STUDY

3.1. General description

The present case study corresponds to a standard Brazilian simple cycle power plant which uses a GE LM6000 aeroderivative gas turbine which power capacity at ISO conditions is equal to 42.75 MW. The LM6000 turbine consists of a five-stage low-pressure compressor, a 14-stage high-pressure compressor, a two-stage air-cooled high-pressure turbine, and a five-stage low-pressure turbine. The overall compression ratio is 29 to 1. However, for purposes of modeling of the plant, it will be considered that the compression process is performed in a unique compression stage. This same consideration will be taken in account for the case of the expansion process occurring in the gas turbine. Thus, the plant configuration of this specific power plant can be analyzed using the PAT model due to its similarities with the basic plant configuration used in the development of the PAT model. For the analysis of this standard simple cycle power plant, the eight alternatives of power augmentation currently available on the PAT model are utilized. These different alternatives are summarized in Table 1.

Table 1. Options of power augmentation techniques available on the PAT model

Option 0:	Base case (without power augmentation)
Option 1:	Fogging
Option 2:	Evaporative Cooling (media-based cooler)
Option 3:	Mechanical Refrigeration
Option 4:	Absorption Cooling
Option 5:	Fogging and Absorption Cooling
Option 6:	Steam injection in the Combustor
Option 7:	Fogging and Steam injection in the Combustor
Option 8:	Fogging, Absorption Cooling and Steam injection in the Combustor

The base case, which corresponds to the option 0 in Table 1, refers to the plant configuration which does not use any power augmentation technique. The results obtained for this base case are used as reference for comparing simple cycle performance and economics for the other options evaluated. The main thermodynamic parameters assumed for the simulations and analyses of the simple cycle power plant corresponding to the present case study, including the ambient conditions, are shown in Table 2.

Table 2. Main thermodynamic parameters assumed on the simulations of the CCPP

Ambient temperature (Dry bulb)	28.0	°C
Ambient pressure	101.0	kPa
Relative humidity	80.0	%
Pressure ratio	29.0	---
Air mass flow rate	121.45	kg/s
Compressor isentropic efficiency	87.0	%
CC pressure drop	5.0	%
Combustion efficiency	99.0	%
Turbine inlet temperature, TIT	1115.0	°C
Turbine isentropic efficiency	89.5	%
Exhaustion pressure drop	2.0	%
Fuel (natural gas) LHV	50.84	MJ/kg
Power output loss factor	0.02	---
Mechanical efficiency	99.0	%
Generator efficiency	99.0	%

In turn, Table 3 shows the main economic assumptions on which are based the analyses of the economic feasibility of the implementation of the different alternatives of power augmentation studied here. In this table, the operation hours by year indicated correspond to the annual amount of operation hours of the power augmentation system installed in the power plant. Also, it is important to emphasize that escalation rate for fuel price and water cost was not considered.

In addition to the economic assumptions shown in Table 3, it was also assumed specific costs for each cooling system analyzed in this work. Table 4 shows the specific costs assumed for each alternative of power augmentation available on the PAT model in $ per kW of power output added to the simple cycle power plant. These values were derived from the typical ones used in literature (Ameri *et al*., 2004, Boyce, 2002, Kakaras *et al*., 2004, Al-Bortmany, 2002, Cortes and Willems, 2003, and Sanaye *et al*., 2004). The specific costs of the alternatives of power augmentation involving the combination of two or more power augmentation techniques were estimated by a weighing process involving the power output increase obtained and the specific cost associated with each of them. The Purchased-Equipment Cost (PEC) of each cooling system was calculated as the difference between the assumed specific cost and the equipment installation cost, which was assumed as being equal to 30% of the PEC. The annual maintenance cost of each cooling system was assumed as being equal to 10% of the PEC, and with an increase per year of 10%.

Table 3. Economic assumptions

Fuel price (Natural gas)	0.0038	$/MJ
Demineralised water price	0.50	$/m3
Operation hours per year	2920	h/yr
Capacity factor	97.0	%
Price of electricity	0.065	$/kWh
Financing cost	12.0	%
Term (repayment)	20	yr

Table 4. Specific costs for each cooling method available on the PAT model

Option 1	50.0	$/kW added
Option 2	35.0	$/kW added
Option 3	200.0	$/kW added
Option 4	300.0	$/kW added
Option 5	191.7	$/kW added
Option 6	100.0	$/kW added
Option 7	65.7	$/kW added
Option 8	187.3	$/kW added

3.2. Results and discussion

First of all, in order to accurately evaluate the influence of the different alternatives of power augmentation on the power output and thermal efficiency of the simple cycle power plant being analyzed, the PAT model was adjusted through variations of the isentropic efficiencies of the main components of the gas turbine, and through the setting of data related to the flue gases conditions (mass flow and temperature) at the turbine exhaust provided by the manufacturer of the same. Thus, the simulation of the gas turbine using the PAT model, considering ISO ambient conditions, resulted on a shaft power output of 42.92 MW, which corresponds to a difference of about 0.4% of its ISO power output (42.75 MW).

Once the PAT model was adjusted considering the particular characteristics of the gas turbine, the next stage of this study was to simulate the simple cycle power plant, but this time including the different alternatives of power augmentation available on the PAT model. Thus, Figure 4 shows the percentage variations of both the net plant output and net plan efficiency when these methodologies of power augmentation are utilized. Each option shown in Figure 4 corresponds to one particular methodology of power augmentation available on the model, such as detailed in Table 1. Yet in Figure 4 it is possible to see that the inlet air cooling through the use of the fogging system, option 1, originates an increase of the order of 2.6% on the net power output of the plant. However, the plant thermal efficiency is only slightly increased. A similar behavior to the case of the fogging system is observed when the evaporative cooling system, option 2, is utilized to cool the inlet air. The smaller improvements obtained in this case, in terms of power output and thermal efficiency, are due to the evaporative cooling system effectiveness, which is lower than that corresponding to the fogging system. The small increases in power output and thermal efficiency obtained by the use of the evaporative cooling systems (options 1 and 2) are originated as a consequence of the ambient conditions assumed for the plant operation, and more specifically as a result of the high relative humidity associated to them. Remembering that the minimum air inlet temperature that could be achieved through the use of these power augmentations systems corresponds to the air wet-bulb temperature (relative humidity of 100%), which for this specific case is equal to 25.2 °C.

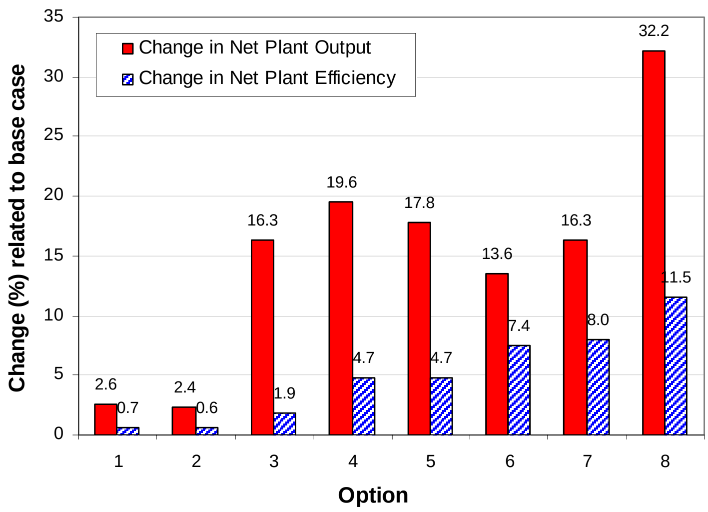

Figure 4. Influence of the different PAT on the net plant output and net plant efficiency

The following three options of power augmentation studied in this work, which correspond to the process of inlet air cooling through the utilization of a mechanical refrigeration system, an absorption cooling system, and a combination of a fogging system and an absorption cooling system, options 3, 4, and 5, respectively, can be analyzed together due to the fact that these power augmentation techniques have a similar behavior from the thermodynamic point of view. In these three power augmentation techniques, the desired exit temperature of the air stream after the cooling system was fixed equal to 8 °C. The use of refrigerated cooling systems (mechanical refrigeration or absorption cooling), such as shown in Figure 4, increases the plant power output significantly. This significant improvement on the power output of the plant is due mainly to the considerable increase of the mass flow rate going through the gas turbine, as a consequence of the lower gas turbine inlet temperature. In Figure 4, it is also possible to observe that use of these cooling systems increases the plant thermal efficiency. The increases on the thermal efficiency of the plant are not as significant as on the case of the power output due to the greater amount of fuel consumed by the plant. This last is originated as a consequence of the greater air mass flow entering to the combustion chamber and to the turbine inlet temperature, which was maintained constant during the plant simulations. The combined use of a fogging system and an absorption cooling system (option 5) has a similar behavior to the two options previously analyzed. The main difference is related to the smaller increase on the inlet air mass flow, due to first the addition, and then the removal of water mass flow of the air stream, which, consequently, originates a smaller improvement on the power output and the thermal efficiency of the plant.

The steam injection in the combustor chamber (option 6), the amount of which was limited to 3% of the inlet air mass flow in our analysis, resulted also in a considerable increase of both plant power output and plant thermal efficiency. As observed in Figure 4, this option of power augmentation leads to a greater increase of the plant thermal efficiency than the options previously analyzed. This last is originated as a consequence of the use of the energy available on the stack gases that otherwise would be wasted. These results confirm what is well known, steam injection is very effective for simple cycle gas turbines, but for combined cycle power plants, steam can generate more work in the steam turbine. Results of the use of the PAT model to analyze the influence of different power augmentation techniques on performance of a specific combined cycle power plant were presented by the authors in a previous conference (Celis *et al*., 2007).

The two last options of power augmentation studied in this work (options 7 and 8) add, first, an inlet fogging system, and second, and inlet fogging system and an absorption cooling system, to the steam injection in the combustion chamber. In the first case (option 7), the reduction of the inlet air temperature, through the use of a fogging system, originates a increase of the mass flow rate going through the gas turbine and a decrease of the specific compression work, whose total effect on the plant performance is more beneficial than the increase of the fuel consumption. This behavior can be observed in Figure 4, which shows an increase of not only the net plant output but also the net plant efficiency. In the second case (option 8), the additional inclusion of an absorption cooling system for cooling the inlet air flow lead to significant additional gains on the net plant output and the net plant efficiency. This last is owing to the considerable increase of the mass flow rate which goes through the gas turbine, as a consequence of the significant reduction of the gas turbine inlet temperature.

It is interesting to note that the increases on plant thermal efficiency are not as significant as the gains obtained for the case of the plant power output. This is emphasized by the fact that the use of these power augmentation techniques originates an increase of not only the plant power output but also the plant fuel consumption. In other words, the increase in thermal efficiency is smaller than that corresponding to the plant output because the compressor outlet temperature drops, imposing a larger temperature difference between the inlet and the outlet of the combustor, consequently, more fuel must be added. This last is illustrated in Table 5, which shows the influence of the use of the power augmentation techniques on the mass flow rate and the temperature of the gas turbine working fluid at the stations 1, 2, and 3 shown in Figure 1. In this table, the percentage changes of the temperature and the mass flow rate related to the values of the base case are indicated in the parentheses.

Table 5. Influence of the power augmentation techniques on the operating conditions of the GT working fluid

Option	Temperature [K]		Mass flow rate [kg/s]	
	Station 1	Station 2	Station 1	Station 3
Base	301.2	828.9	115.0	116.9
1	298.4 (-0.9 %)	821.7 (-0.9 %)	115.9 (0.9 %)	117.9 (0.9 %)
2	298.7 (-0.8 %)	822.4 (-0.8 %)	115.9 (0.8 %)	117.8 (0.8 %)
3	281.2 (-6.6 %)	780.8 (-5.8 %)	124 (7.9 %)	126.2 (8 %)
4	281.2 (-6.6 %)	780.8 (-5.8 %)	124 (7.9 %)	126.2 (8 %)
5	281.2 (-6.6 %)	780.8 (-5.8 %)	122.2 (6.3 %)	124.3 (6.4 %)
6	301.2 (0 %)	828.9 (0 %)	115 (0 %)	120.4 (3 %)
7	298.4 (-0.9 %)	821.7 (-0.9 %)	115.9 (0.9 %)	121.5 (3.9 %)
8	281.2 (-6.6 %)	780.8 (-5.8 %)	122.2 (6.3 %)	128.1 (9.6 %)

Regarding the determination of the investment economic indicators, which allow evaluating the economic performance of the investment related to the implementation of any of these power augmentation alternatives analyzed, Figure 5 and Figure 6 show, respectively, the internal rate of return of the investment, as well as the investment net present value and the pay-back period in which the investor could recover his investment.

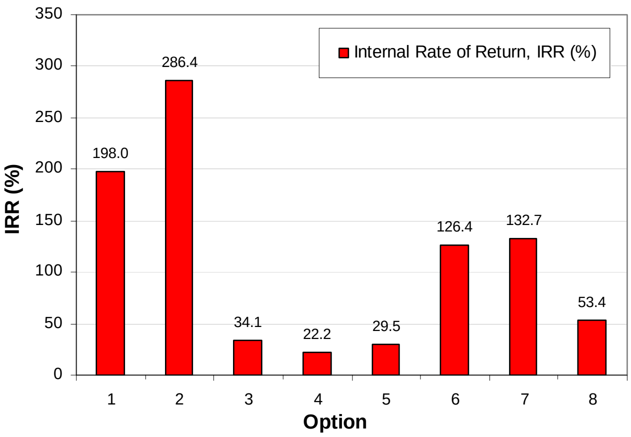

Figure 5. Internal rate of return related to the PAT implementation

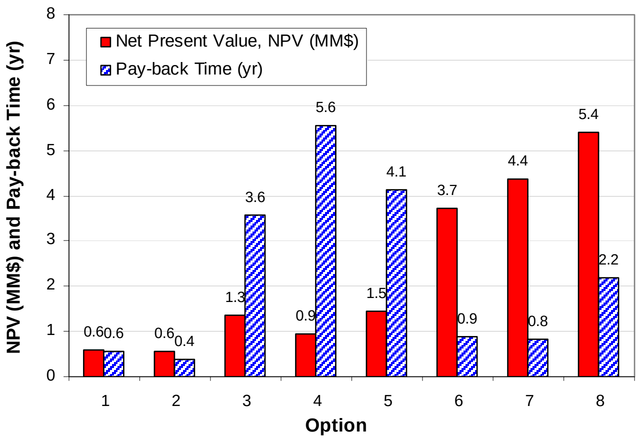

Figure 6. Net present value and pay-back time related to the PAT implementation

The highest values of the IRR shown in Figure 5, which correspond to the two first options of power augmentation analyzed, are originated as a consequence of both the low specific costs associated to the implementation of each power augmentation technology, and the relatively considerable increase on the power output and thermal efficiency of the simple cycle power plant. Even though the last options of power augmentation originate increases on the plant power output and thermal efficiency which are greater than those corresponding to the two first options, the internal rate of return is smaller, because of the greater specific costs associated with these methodologies of power augmentation. This type of behavior associated to the IRR is reflected oppositely on the pay-back time, as expected, Figure 6, i.e., the first two options of power augmentation present pay-back periods which are smaller than those related to the implementation of the last power augmentation techniques analyzed in this work.

With relation to the net present value which represents the implementation of the different methodologies of power augmentation studied, the considerable power output and thermal efficiency increases of the power plant originates NPVs which are proportional to the gains obtained on these plant performance parameters. Thus, the last three options of power augmentation analyzed (options 6, 7, and 8), which regard to the use of a system of steam injection in the combustor and the later addition of an inlet fogging system and an absorption cooling system, present NPVs which are considerable greater than those corresponding to the other options. This last is due mainly to the significant increases on the net plant efficiency obtained through the use of these options of power augmentation.

4. CONCLUSIONS

In this work, a computational program, called PAT model, was developed to carry out thermal performance and financial analysis for modeling of either simple or combined cycle power plants. The PAT model was subsequently utilized to analyze a case study corresponding to a standard Brazilian simple cycle power plant. Different alternatives of power augmentation currently available on the PAT model were considered on the simulations, and their influence on the plant performance was analyzed. The results of the simulations indicated that significant improvements, in terms of power output and thermal efficiency, can be achieved through the use of all the power augmentation techniques employed. In particular, the results showed that the use of power augmentation systems based on refrigerating process with (option 8) and without steam injection in the combustor (options 3, 4, and 5) produces the greatest gains in terms of net plant output and net plant efficiency. These results confirm the suitability of these power augmentation systems for the cases of humid and hot ambient conditions, as those considered on this work, as well as for plant configurations of the simple cycle type.

From the economic analysis, it can be concluded that depending of the level of importance of the economic indicators computed, internal rate of return, net present value, and pay-back period, some alternatives of power augmentation could result more attractive than others. So, the plant owner is the only one who can decide which alternative would be the most suitable for his interests. For the specific simple cycle power plant analyzed in this case study, and considering the net present value as the main parameter determining the implementation of a project of this category, it can be concluded that the alternatives of power augmentation including a system of steam injection in the combustor (in order of importance, options 8, 7, and 6) are the most appropriated for this plant. Following this same criterion, the other options of power augmentation that should be considered for this specific plant are those based on the use of refrigerated inlet cooling systems, i.e., options 3, 4, and 5. Finally, the choice of the most appropriated power augmentation technology, which could be used for increasing the plant power output, should be analyzed more carefully through the consideration of other factors such as variations on the fuel and electricity prices, variations on site ambient conditions, water availability, among others, in order to maximize the termoeconomic performance of the simple cycle power plant. The balance between high thermal efficiency and more power output will be dictated by market scenarios. A power augmentation technique that mainly impacts in efficiency can be more suitable for markets with high fuel prices. The same rationale can be adopted for markets with high electricity prices, regarding power augmentation technologies that have more influence on power generation.

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