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PERFORMANCE ANALYSIS OF A COMBINED CYCLE FOR ELECTRICITY GENERATION WITH GAS TURBINE COMPRESSOR INLET AIR COOLING BY EVAPORATIVE COOLING

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Abstract. Thermoelectric plants have gained increased attention in the last decades at Brazil. The increase in demand for electric power generation and the search for reliability in the energy sector contributed for it. They have more flexibility and possibility of installation near consumption areas, instead of the hydroelectric plants which have to be installed near a river or large places because of their reservoirs. Since they are a non-renewable source of electric generation, thermoelectric plants have to cause less environmental impacts as possible and so, a study of possible gains in electricity generation and efficiency in a combined cycle through the use of inlet air cooling system for the gas turbine compressor using an evaporative cooling method was performed in this work. The model utilized was previously validated by Rodrigues and Wander (2016) and was used as the base for this study. The cooling method designed was an evaporative cooling system applied in a TRY(Test Reference Year) for the metropolitan region of Porto Alegre, Rio Grande do Sul and Mossoró, Rio Grande do Norte, Brazil. The results show the influence of the inlet air cooling for an increase in electric power generation, and is possible to see this influence specifically at summer months which have lower relative humidity than winter ones, that is a great point since the generation is prejudiced mainly at higher temperatures. The gains in Porto Alegre reached values of power generation increase up to 11.9 MW and Mossoró up to 11.5 MW. For the whole year the electric power generation had an increase of 17 GWh for Porto Alegre and 30 GWh for Mossoró, which had the highest increase with addition of evaporative cooling system, because of its climate. The Power Plant average efficiency had an increase of 1.4% for Mossoró and 0.7% for Porto Alegre.

Keywords: Gas Turbine. Combined Cycle. Energy. Thermal Systems

1. INTRODUCTION

The water resource is abundant in Brazil, then the main source of electricity generation is hydropower, which, according to the National Energy Balance (EPE 2017) report, corresponded to 64.5% of the domestic electricity supply in 2016. But with technological developments, efficiency and thermal reliability increases, generation scenario in Brazil is changing gradually.

Since the 2000s, the growth of the thermoelectric participation in power generation is remarkable, according to the National System Operator (ONS, 2017) the average monthly thermal generation in 2017 was 9477.8 GWh, while in 2000 this figure was only 1252.57 GWh/month, indicating a growth of 657%. However, the hydroelectric generation grew by only 19.5% in the same period, ranging from 27965.56 GWh/month, in 2000, to 33421.67 GWh/month in 2017.

Because it is a non-renewable energy source, often the thermal energy becomes much more expensive compared to others. So, to extract the maximum performance in thermal power plants, project optimizations, improvements in equipment, materials, transmission lines are made and also the combination of different generation sources.

Being a country with a tropical climate, Brazil has high temperatures most part of the year, which ends up harming the thermodynamic cycle, as the efficiency and the energy generated by a gas turbine is directly influenced by the pressure, temperature and humidity in compressor air inlet. The temperature has the greatest influence on the energy generation, the higher the temperature the lower will be the generated power. (Carvalho Junior, 2012).

To enhance the power output it's necessary to increase the mass flow of air entering the compressor, which could be caused by a drop in inlet temperature and the consequent density increase. In this sense, as the air inlet temperature drops, compressor work decreases and so the net work and cycle efficiency increases. (Mohapatra and Sanjay, 2013)

2. LITERATURE REVIEW

2.1 Combined Cycle

According to Çengel and Boles (2001) gas turbines operate in the Brayton thermodynamic cycle. In this cycle, the ambient air enters at the gas turbine, it passes through a compressor to get pressure increase. Fuel is then injected into the high-pressure air and ignited in the combustion chamber. The combustion's hot gas mass flows to the turbine section and produces the work in turbine shaft to drive the generator shaft and so generate electricity. Part of the generated work is also used to drive the compressor. The hot gas leaves the turbine, and in a combined cycle, it passes through a heat recovery steam generator (HRSG) to recover part of its wasted heat. The generated steam is used in a steam turbine to generate electricity, by the Rankine cycle.

Kehlhofer et al. (1999) states that when two thermal cycles are combined in a generation plant, the efficiency that can be achieved is higher than the simple cycle. By combining two cycles, the cycle that works at a high temperature is called topping cycle and the cycle that works with the topping cycle rejected temperature is called bottoming cycle. The most developed kind of combined cycle is between the Brayton and Rankine cycle. Boyce (2010) states that the thermal performance can reach values very close to 60%, with the use of a combined cycle.

2.2 Gas Turbine Inlet Air Cooling

Çengel and Boles (2001) explains that the compressor power consumption depends on the ambient temperature, and states that for every 3 °C of decrease in ambient temperature the power consumed by the compressor decreases by 1%, increasing the efficiency of the cycle. Sa and Zubaidy (2011) demonstrated in tests on gas turbines that each 1 °C increase in ambient temperature, above ISO conditions, involves the reduction of 0.1 % in thermal efficiency of the tested turbines.

As mentioned, the compressor inlet air temperature is one of the most influent aspect in the efficiency and power delivered by the gas turbine. This is because the air specific volume is proportional to its temperature, thus decreasing the air entering mass flow in warmer ambient conditions, since the turbine is a machine that works at constant volume.

According to Kehlhofer et al. (1999) as the air specific volume is higher at elevated temperatures the compressor mass flow is reduced, so the gas turbine mass flow will also affect the amount of energy passing through the HRSG.

The conditions set for the design of gas turbines are ISO conditions (ambient temperature of 15 °C, relative humidity of 60% and air pressure of 101.3 kPa) (GE, 2003) . These conditions are rarely found in tropical countries, such as Brazil. According to INMET (2018) data for the state of Rio Grande do Sul, more precisely in the Porto Alegre region, the annual average measured in 1961-2017 is 20.8 °C and for Mossoró, Rio Grande do Norte, is 28.5 °C. The maximum average temperatures are around 25.4 °C with peaks of 39.3 °C in summer for the first and 28.7 °C with peaks of 35 °C for the second one, which means a considerable difference to the design conditions. The annual relative humidity average is about 74.8% at the summer at Porto Alegre and about 66% at Mossoró.

According to Boyce (2010) to perform the compressor inlet air cooling some methods can be used, but the most common are the evaporative method, absorption cooling method or mechanical vapor compression with thermal energy storage method.

Jonsson and Yan (2005) classified the available inlet air cooling systems into the following groups:

- Evaporative Media Coolers: Water is distributed over saturated evaporative cooling media through which the air passes to be humidified;
- Spray inlet coolers or fogging systems: Water is injected into the air through nozzles, located in the compressor inlet, and creates a fog of small water droplets.
- Mechanical vapor compression or absorption chillers, where a heat exchanger cools the inlet air. Chillers can increase the gas turbine power output by 15 - 20% and the efficiency by 1- 2% (i.e. if gas turbine exhaust gas energy is recovered). A chiller can cool the inlet air regardless of the ambient conditions; however, the specific investment cost is much higher than for evaporative media and spray coolers.

The cooling method selected for this study was the method of cooling by evaporative media cooling.

Boyce (2010) states that Evaporative coolers consist of water being sprayed over media blocks made of fibrous corrugated material. The airflow through these media blocks evaporates the water, which needs latent heat of vaporization taken from the air itself, causing a decrease in air temperature entering the compressor.

Oyedepo e Kilanko (2014) found in their results for a simple cycle with one gas turbine that for each 5 °C decrease of inlet air temperature net power increases around 5-10% and the thermal efficiency increases around 2-5%.

Jonsson and Yan (2005) described that a evaporative media cooler can increase the relative humidity of the air to about 90%, thus increasing the power output by 5 − 10% and the efficiency by 1.5 − 2.5%.

3. METHODOLOGY

To attend the objective of this work a thermodynamic model developed by Rodrigues and Wander (2016) was used for the calculation of efficiency and power generated with and without gas turbine compressor inlet air cooling.

Efficiency calculations were made using computer modeling in the EES (Engineering Equation Solver) software and collection of the actual cycle operation data in a thermal power plant in the metropolitan region of Porto Alegre, Rio Grande do Sul, was used to validate the model. For the inlet air cooling, literature data were used.

The methodology to obtain the results was through the following steps:
- Survey of the equations for the model construction;
- Acquisition of actual data system operation;
- Insertion and model arrangement in EES software;
- Apply the climate data for Porto Alegre, RS, and Mossoro, RN, on the model.

The climate data has 8760 hours of a TRY data and all hours were utilized for the simulation.

Figure 1 show cities location.

Figure 1. Brazilian Climate map with Porto Alegre and Mossoró. (Adapted from IBGE, 2016).

The model validation by Rodrigues and Wander (2016) for different compressor inlet temperatures allow considering valid the cooling method. To determine the system's behavior over a full year, dry bulb and relative humidity of a typical year in the region of Porto Alegre, RS, and Mossoró, RN, were chosen. The typical year for a region is generated by a TRY (Test Reference Year) file, in which data is generated by the elimination of years with extreme temperatures over a long term database, until remain only a single year called the reference year. This cities were chosen because one has a humid and cold winter and the other has a dry and hot weather over the year. According to IBGE (2016) Porto Alegre has a super humid climate and mesothermic mild temperature (average of 10 ºC and 15 ºC) and Mossoró has a semi-arid climate and hot temperature (average higher than 18 ºC over the year). Both cities have very close altitudes: Porto Alegre is 8 m and Mossoró is 20 m above sea level. This is important due to the influence of altitude at power generation by combined cycles.

3.1 Thermoelectric Plant

The thermoelectric plant used as base for this study is located at the metropolitan area of Porto Alegre, Rio Grande do Sul, Brazil. The plant physical installation arrangement is similar to that in Fig. 2a, which has a GE MS7001FA gas turbine, an ANSALDO HRSG (Heat Recovery Steam Generator) with three pressure levels and a Siemens SST-700/SST- 900RH steam turbine (double axis and double case). The addition of the evaporative cooling system in gas turbine is shown at Fig. 2b. The gas turbine is responsible for the production of 166.3 MW at ISO conditions, operating with OCTE (Oil Fuel for Electric Turbine), and the steam turbine is responsible for producing 86.3 MW.
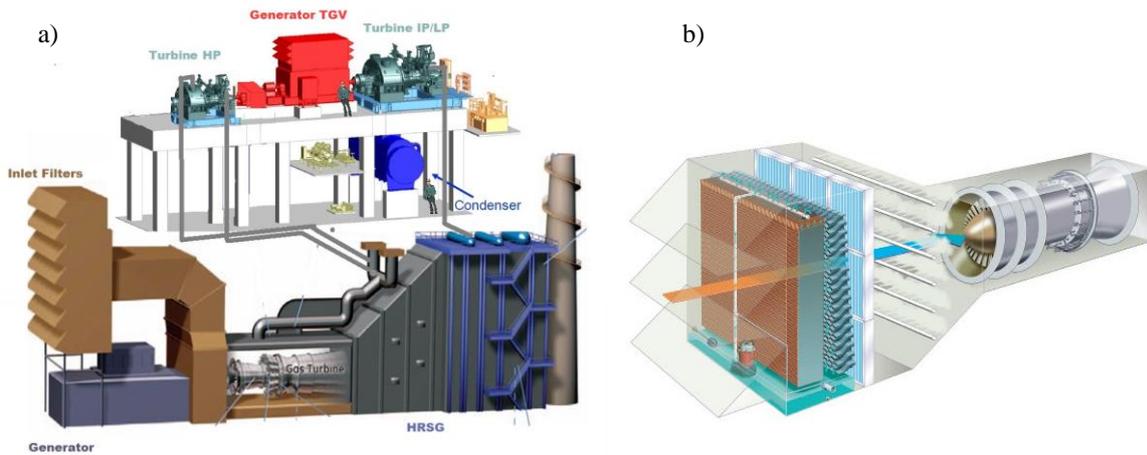
Figure 2 – (a) General Combined Cycle Plant Installation.(Adapted from Siemens, 2009). (b) Evaporative cooling installation. (Adapted from Munters, 2015).

3.2 Humidifier Model

As has been explained, in the evaporative cooling air passes through a media with water or a spray of water, where the inlet air, with a low humidity, evaporates the water and decreases his temperature. The outlet air of the humidifier has a high humidity, and it depends on the effectiveness of media.

The relative humidity (ϕ) is represented for eq. 1:

$$\phi = \frac{P_w}{P_{ws}} \tag{1}$$

ASHRAE (2009) states the humidity ratio (w) as follow the eq. 2:

$$W_0 = 0.621945. \frac{P_w}{P - P_w} \tag{2}$$

Where W_0 is the incoming air humidity ratio, P_w is the partial vapor pressure, and P is the atmospheric pressure.
For the temperature range of 0 to 200 °C the saturation pressure over liquid water is defined by eq. 3:

$$ln(P_{ws} . 1000) = \frac{C1}{DBT_0} + C2 + C3.DBT_0 + C4.DBT_0^2 + C5.DBT_0^3 + C6.ln(DBT_0) \tag{3}$$

Where P_{ws} is the saturation pressure of water, DBT_0 is the absolute dry bulb temperature, and the coefficients C are as follow: C1 = −5.800 220 6 E+03; C2 = 1.391 499 3 E+00; C3 = −4.864 023 9 E−02; C4 = 4.176 476 8 E−05; C5 = −1.445 209 3 E−08 and C6 = 6.545 967 3 E+00. The temperature must be in K.

According to Johnson (1989) eq. 4 can be used to determinate the first approximation of the new Dry Bulb Temperature (DBT_1):

$$DBT_1 = DBT_0 - \eta_{evap}.(DBT_0 - WBT) \tag{4}$$

Where DBT_1 is the dry bulb temperature of air leaving the evaporative cooler, η_{evap} is the evaporative cooler effectiveness, which for this work is defined as 0.9, and WBT is the wet bulb temperature.

There is a pressure drop caused by the air flowing through the rigid media, which has an influence at the generated power, and it has to be calculated.

Munters (2015) shows the performance of a 300 mm depth rigid media for gas turbines, as could be seen at Fig. 3.
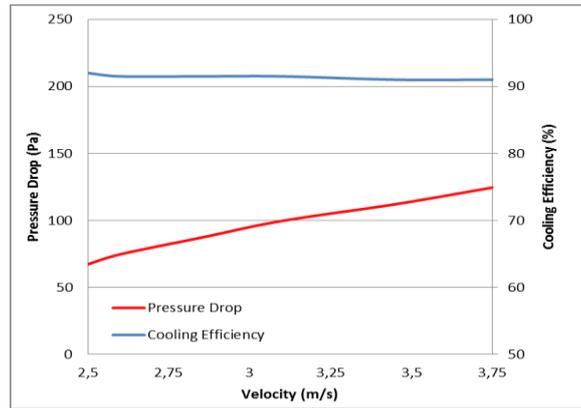
Figure 3 – 300 mm TURBOdek evaporative media performance curve (Adapted from Munters, 2015).

To correct the influence of pressure drop was generated eq. 5, which describe the curve presented by Munters (2015), with a R²=0.9982, in function of compressor inlet air velocity.

$$\Delta P_{mrig} = -10.39 V_{air}^{2} + 109.55 V_{air} - 140.73 \tag{5}$$

The enthalpy is calculated by eq. 6 and eq. 7:

$$h_0 = 1.006\, DBT_0 + (2501 + 1.86\, DBT_0)W_0 \tag{6}$$

$$h_1 = 1.006\, DBT_1 + (2501 + 1.86\, DBT_1)W_1 \tag{7}$$

Where W_1 is the moist humidity ratio of air leaving the evaporative cooler.
Johnson (1989) defined the volumetric water evaporation rate $\dot{E}_w$ by eq. 8.

$$\dot{E}_w = \dot{V}_{air}.(W_1 - W_0).\frac{\rho_{air}}{\rho_w} \tag{8}$$

Where W_0 is the moist humidity ratio of inlet air and V_{air} is the volumetric air flow, ρ_{air} is the density of air and ρ_w is the density of injected water.
When the evaporative cooler water is delivered above the WBT of the air we have a nonadiabatic cooling process, then we have to consider the sensible heat of water cooling until the WBT. This is calculated by eq. 9 that will give the final DBT of the air leaving the evaporative cooler.

$$DBT_2 = DBT_1 + \frac{\dot{Q}_w}{Cp_{air}.\dot{m}_{air}} \tag{9}$$

Where DBT_1 is the dry bulb temperature of air leaving the evaporative cooler, if the process was adiabatic, DBT_2 is the final dry bulb temperature of air leaving the evaporative cooler, Q_w is the thermal energy flow rate from water to air, which is defined by Eq. 10, Cp_{air} is the specific heat of the air and m_{air} is the air mass flow.

$$\dot{Q}_w = \dot{m}_w Cp_w(T_w - WBT) \tag{10}$$

Where $\dot{m}_w$ is the water mass flow rate, Cp_w is the specific heat of the water and T_w is the temperature of water.
To obtain the dry air mass flow, eq. 11 was used.

$$\dot{m}_{da} = \frac{\dot{m}_{air}}{1 + W_0} \tag{11}$$

Where m_{da} is the dry-air mass flow.

4. RESULTS

The results described in this chapter were obtained from the EES designed model and the input data from the actual process such as compressor suction and discharge pressure, the turbine inlet temperature, compressor inlet volumetric air flow, air/fuel ratio and HRSG steam flow and pressure.

Through Fig. 4 is possible to see the ambient temperature influence in the behavior of electrical power generation. It's clear that in the winter months the generation has an increase if compared with the summer months, which are represented by the chart corners. The trend lines show graphically this influence.
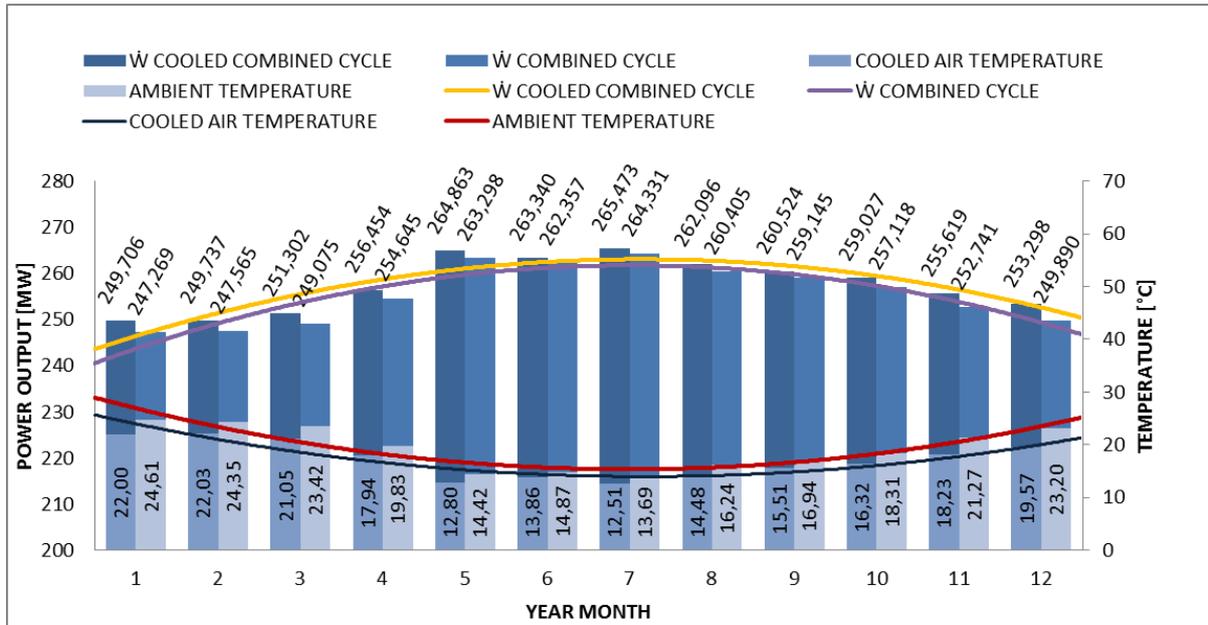

Figure 4. Average power generation and temperature by month for a typical year at Porto Alegre, RS.

It's possible to see in the summer months that the evaporative cooling system is more effective. This occurs because of its lower relative humidity than the winter months where there is a small difference between the cooled and the non-cooled air. This difference can be observed at the power generation too, which has a behavior like the trend of the temperature.
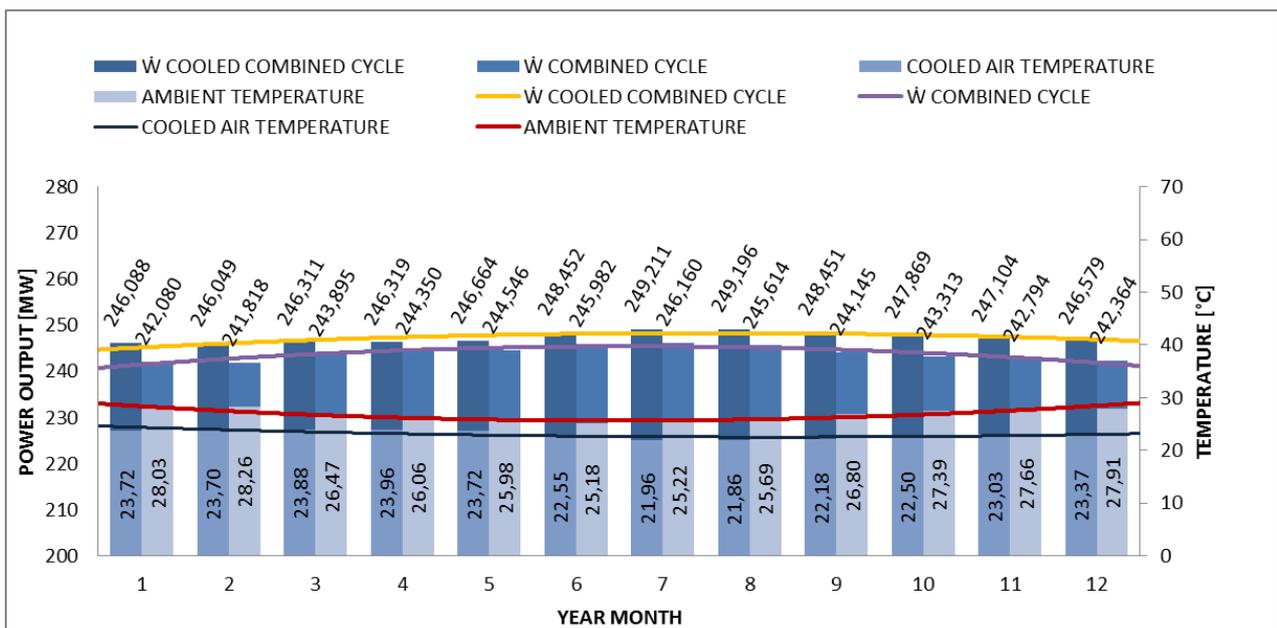

Figure 5. Average power generation and temperature by month for a typical year at Mossoró, RN.

Figure 5 shows the behavior of power generation at Mossoró, RN, where the ambient temperatures are higher than Porto Alegre. The Cooled combined cycle power generation is more stable over the year while the normal cycle has a little worsening at summer. It's explained by the higher ambient temperatures, which is adjusted by the cooling .The difference between power generation in each case is perfectly noted at fig. 5, where the power generation increase is proportional to the air inlet temperature decrease.

For this simulation all data from both TRY files were used to generate a month average, which were compiled in bars for better viewing.

Comparing Fig. 4 and Fig. 5 it's possible to see the higher gain for Mossoró than Porto Alegre. It occurs because of the lower relative humidity for the region. While Porto Alegre has a higher generation because of its lower temperature, Mossoro shown a higher generation gain with the evaporative cooling because its semi-arid climate. But, as both graph at this figures have the same scale on their axis, it's possible to see the major power generation capacity in Porto Alegre, because of the lower ambient temperatures. At a whole year it represents a difference of 4.16% more generation in Porto Alegre than Mossoró with cooled cycle, while without the evaporative cooling system this difference increase to 4.8%, which is a reasonable value, i.e., the evaporative cooling system is able to decrease the difference in generation capacity for different locations.
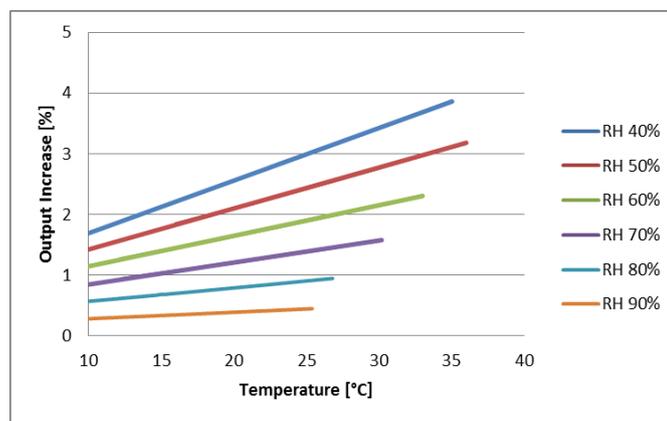

Figure 6. Power increase for various ambient temperatures and relative humidity.

It's possible to see at Fig. 6 the behavior of plant power output increase for different relative humidity by function of temperature. It's clear that the lower the relative humidity, the greater will be the gain. It occurs because of the evaporative cooling principle, where the air passing through the rigid media has a larger capacity to evaporate the falling water, and when ambient temperature is higher, cooling results are better.

The major gain at Porto Alegre is 4.95% at Rh 20% and ambient temperature 30.5 °C, which corresponds an increase of 11.96 MW for the given temperature. In Mossoró the best point is 4.90% at Rh 27% and ambient temperature 34.6 °C, which mean an increase of 11.50 MW. The main values for each cycle are shown at table 1.

Table 1. Stratification of the main simulated values.

		DBT [°C]	WBT [°C]	Compressor Inlet Air Temperature [°C]	Combined Cycle Power Output [MW]	Cooled Combined Cycle Power Output [MW]	Power Output Increase [MW]
Mossoró	Max Increase of Power Output	34.60	20.47	21.92	234.992	246.496	11.504
	Min Increase of Power Output	20.50	20.05	20.09	252.691	253.084	0.393
	Max Power Output	17.50	16.65	16.74	257.649	258.387	0.738
Porto Alegre	Max Increase of Power Output	30.50	16.01	17.49	241.530	253.493	11.963
	Min Increase of Power Output	5.10	5.03	5.04	278.070	278.134	0.064
	Max Power Output	1.30	1.30	1.30	284.416	284.416	0

Oyedepo e Kilanko (2014), Ameri et al. (2007) and Hosseini et al. (2007) found about 11 MW of maximum gain in their studies, where the last ones had studied plants in Iran and the first one had studied a plant in Niger. The improve of output power for them was about 14%, but if we consider for this study just the simple cycle, the output increase for the higher gain is about 7.1% for both cities, and the major power output increase is near the results found by this authors. The greater increase in output power for the authors mentioned may be explained by the location under analysis, where dry bulb temperatures are above 37 °C and relative humidity are as low as 8%, which provides higher benefits for evaporative cooling usage.

Comparing results with De Lucia et al.(1995), which simulate a cogeneration plant with evaporative cooling in Italy, it's possible to see that values are very close, where was found that the cooling system was able to supply power increases of 2 - 4% on a yearly basis.

Observing table 1 it is possible to note that the maximum increase of power for both cases is at the biggest difference between DBT and WBT, which mean the lower relative humidity. As it was explained before, the simulation has the expected behavior. At the minimum increase of power output the DBT and WBT are near, then the capacity of evaporative cooling is minor. For the maximum power output the result shows that the major influence is the ambient temperature, i.e. as ambient temperature is lower, power output will be bigger.

Table 2 shows the influence of evaporative cooling at cycle efficiencies for both cases. The increase at efficiency is bigger at Mossoró, where the average increase represent 1.4% at combined cycle efficiency, while at Porto Alegre it was about 0.7%.

Table 2. Average Efficiencies of each location.

	Mossoró		Porto Alegre	
	NORMAL	COOLED	NORMAL	COOLED
Global Efficiency Combined Cycle	0.5046	0.5117	0.5135	0.5175
Global Efficiency Brayton Cycle	0.3412	0.3482	0.3509	0.3548
Global Efficiency Rankine Cycle	0.3355	0.3359	0.3336	0.3338

The main gain in efficiency is at Brayton cycle because of direct influence of inlet air temperature at the compressor, while the Rankine cycle has a small increase in its efficiency. It occurs because of exhaust gases temperature at gas turbine, which decreases with evaporative cooling addition, but the water added by cooling process rises the gas mass flow, compensating the temperature drop.

Kakaras et al. (2004) simulated a simple cycle gas turbine with integration of an evaporative cooler and found an increase of 0.44 percentage points in efficiency and 6.8% in power output at high ambient temperatures and relative humidity of 45%. These results are closer to those found at Porto Alegre, which has a lower efficiency increase than Mossoró.

Figure 7 shows the annual increase of electric power generation for each location.
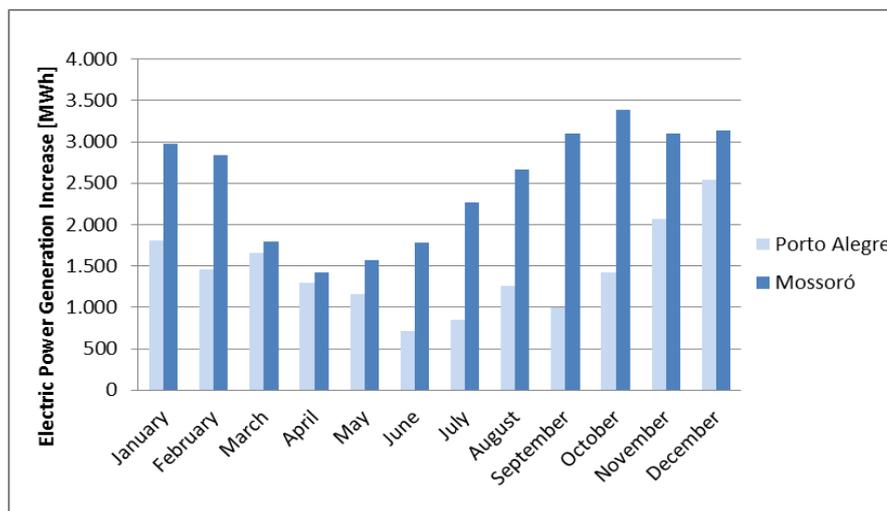

Figure 7. Increased Generation Monthly Capacity with the use of Evaporative Inlet Air Cooling for each location

It can be seen at fig. 7 that the gains in Mossoró are greater than in Porto Alegre due to the local climate, which has lower relative humidity. The increased amount of electric power generation is considerable for both cases, with highlights for Mossoró, where the gain can reach values near 3.5 GWh in October. For Porto Alegre the best result is reached at December where there is an increase of more than 2.5 GWh. Over the year the gain is 17.23 GWh for Porto Alegre and 30.06 GWh for Mossoró.

The results found at this work could be compared with results of Rodrigues and Wander (2016) for Porto Alegre, in which the cooling process chosen was mechanical vapor compression cooling. They found a gain about 74.57 GWh for the whole year and the average power output increase was 5.37%, while using the evaporative cooling it was about 0.7%. The better results with the use of mechanical vapor compression cooling are because of higher cooling capacity and lower climate influence on system behavior, i.e. evaporative cooling has a large dependence on relative humidity and ambient temperature, which could be seen at fig. 6, and the other doesn't.

5. CONCLUSION

The results found with the use of evaporative cooling system for gas turbine represent a very interesting gain, mainly for Mossoró which had an average improve of 1.4% at the power output, reaching gains up to 11.5 MW. Porto Alegre shown an average improve of 0.7% at the power output, but this value is higher at summer months.

It was obtained gains of 30 GWh for Mossoró and 17 GWh for Porto Alegre with the implementation of gas turbine inlet air cooling when considering the whole year. It was verified the possibility of power plant installed capacity expansion without large modifications.

The evaporative cooling method showed most effective results for the dry and hot climate, represented for Mossoró, but even Porto Alegre showing worst results, its power generation increase is considerable. It had a lower result because of humid climate.

This study showed the results of an evaporative cooling installation for a combined cycle and analyzed the behavior for different locations, demonstrating that the climate has a great influence on the results.

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7. RESPONSIBILITY NOTICE

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