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COMBINED CYCLE THERMO-ECONOMIC MODELING WITH INLET AIR COOLING

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Abstract. Power gas cycles benefit in terms of reduced power consumption in the compressor by the use of inlet air cooling techniques. An exergetic analysis is necessary to determine the best form of cooling, considering irreversibilities through the second law of thermodynamics and combining with a thermo-economic analysis, one can arrive at the exergetic cost. In the present research will be carried out the exergetic and thermo-economic modeling of a combined cycle with inlet air-cooling, using evaporative cooling units and absorption refrigeration system. The research will involve different configurations, being the base case without cooling, one case with evaporative cooling system (EC), another with absorption refrigeration system (ARS) with three thermal drives (exhaust gases, live steam and process steam). The fourth case will be the combination of the two types of cooling mentioned. The Engineering Equation Solver (EES) software will be used for the detailed realization of the thermodynamic and exergetic analyzes of the cycle in its different configurations, and through the obtained results it will be possible to perform the thermo-economic analysis, reaching the value of the costs involved in each process. The aim of this study is to compare the results obtained with a view to a better design orientation of these systems. Preliminary results based on the first law, show an increase in overall efficiency of 3% for EC and an average of 7% for ARS, and 6% for the RE and ARS combination.

Keywords: Exergy; Combined cycle, Inlet air cooling, Absorption refrigeration system, Evaporative cooling.

1. INTRODUCTION

The growing world energy demand brings the discussion of the incorporation of renewable energy sources and the increase of efficiency of power systems already installed, making this subject of great importance. According to Fig. 1, British Petroleum estimates an increase in energy demand by the year 2035, the year in which coal, oil and gas will be the most used. Another projection says that the total energy consumption in the world grows around 56% between 2010 and 2040 (Alok and Sanjay, 2015).

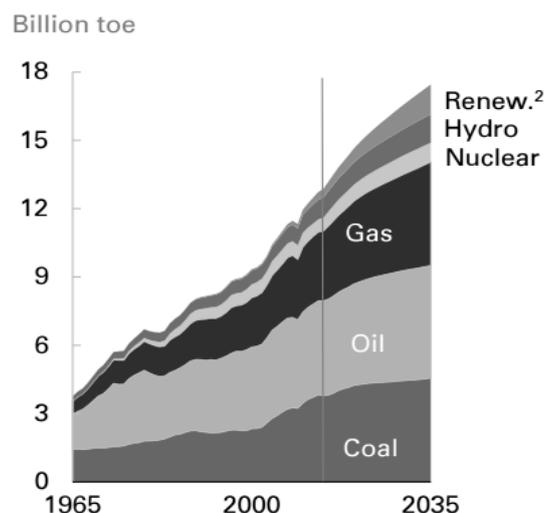


Figure 1. Consumption by type of fuel (BP Energy Outlook 2035, 2015)

The background for the acceptance of new energy sources, as well as new technologies, is based on the costs of energy produced – the costs summed up with certain rates and the entrepreneur's profit margin, compound what is defined as the

price of the energy to be offered in the market (Colpier and Cornland, 2002). Thus, it is important that all initiatives to propose new technological concepts, or those that signal an incremental improvement, are evaluated in terms of the cost of energy produced (assessing, in addition, the other parameters of economic attractiveness).

In view of these issues, the present study aims to analyze the exergy costs of the different energy flows in a combined cycle due to the effects of the cooling of the incoming compressor air. Cooling is a desired effect because with a decrease in temperature, the specific mass of the air increases, thus comprising a higher flow rate present in the gas cycle by the same volumetric flow rate; another desired effect would be a lower power required by the cycle compressor, resulting in both cases an increase in net power generated by the gas cycle, increasing the efficiency. This analysis, to be carried out in a comparative way between different project conceptions, will allow to establish the best decision criteria on the use of steam and exhaust gases for the production of thermal inputs.

Several compressor intake air cooling technologies have been investigated analytically and numerically in the literature, such as Farzaneh-Gord and Deymi-Dashtebayaz (2011), Kim *et al.* 2012, Al-Ibrahim and Varnham (2010) and Najjar and Abubaker (2015). For example, Popli, Rodgers and Eveloy (2013) studied two cases of air cooling from entering a gas cycle, a known thermodynamic method, with the objective of increasing cycle efficiency and generating more electric energy. The results showed a 3.7% increase in cycle energy efficiency for a temperature range of 45° C using the ARS, while evaporative cooling lowered the temperature by 5° C, increasing the yield by 0.4%.

Another benefit would be the approach the temperature of the incoming air with the temperature of the ISO condition of gas turbines (15°C), according to Fig. 2, the efficiency decreases in higher temperatures.

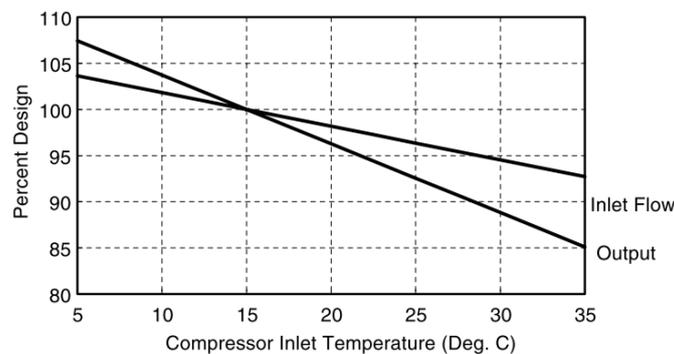


Figure 2. Gas turbine Performance curves (Ameri and Hejazi, 2004)

From the exergetic concepts, it is possible to define the cost structure of the energies produced on a basis closer to reality, since the losses arising from the second law of thermodynamics are discounted from the energy flows, from different way to that which is obtained using the first law of the Thermodynamics. Fallah *et al.* 2016, for example, performed an exergetic analysis on a gas cycle with evaporative cooling of the compressor inlet air, among other conceptions, aiming to establish the percentages of exergy destroyed in each component of the cycles studied as a way of improving the conditions of design and operation of such equipment. Freire, Matelli and Balestieri (2016) used the exergy analysis, in the context of a model for the evaluation of environmental costs by carbon emission, applying it to several configurations of combined cycle (natural gas and sugar cane bagasse).

2. METHODOLOGY

The study will analyze a modeling combined power cycle, using natural gas as main fuel, by comparison, using a base case without refrigeration with three other cases, the first one (Case 1) based only on the insertion of an evaporative cooling unit (with a decrease in the air temperature at the compressor inlet as a consequence of the evaporation of the mass of water and consequent reduction of the temperature of the air) in the air inlet of the compressor, and the second (Case 2) only with the insertion of a absorption refrigeration system unit, which is activated by the system itself. In Case 2, different ways of thermal drive of the refrigeration cycle will be tested: through the exhaust gases of the gas turbine (Case 2a); through the high pressure steam produced in the recovery boiler (Case 2b); through the medium pressure steam obtained in the extraction of the steam turbine (case 2c). The operation of each kind of refrigeration system is described in section 2.1 and 2.2.

The third configuration (Case 3) is the one that uses the evaporative cooling integrated to an absorption refrigeration system, subdivided again in Case 3a, Case 3b, Case 3c, due to the kind of thermal activation of ARS.

The section 2.3 will describe the combined cycle with further details, with all configurations cited.

The laws and concepts of thermodynamics will be applied to each of the configurations, such as mass and energy conservation, at the input and output of each unit present in the process, using EES software to simulate configurations and obtain results of technician character.

The next step is to construct an exergetic analysis for each flow in each configuration. By treating air as the ideal gas, we can use Eq. (1), according to Kotas (1985), for the specific exergy of gas-to-gas flows, and Eq. (2) was used for the specific exergy of flows from cycle a steam, where variables with index "0" indicate their value relative to the environment where the system is, and index "i" of the value referring to its value at that point in the process.

$$b_i = C_p * \left(T_i - T_0 - T_0 * \ln\left(\frac{T_i}{T_0}\right) \right) - R * T_0 * \ln\left(\frac{P_i}{P_0}\right) \quad (1)$$

$$b_i = (h_i - h_0) - T_0 * (s_i - s_0) \quad (2)$$

From these data, the exergetic cost balance equations will be developed for each of the configurations in order to estimate the unit exergetic cost of the energy flows present in them. The exergy model elaborated in Lozano and Valero (1993) and Valero *et al.* (1994), called Thermoeconomic Exergetic Cost (TEC), will be used to determine the exergy costs of the energy flows present in each configuration studied in the three cases and their derivations.

The TEC uses the Eq. (3) to determine the unit exergetic cost "k" of a physical flow point. Where "B*" is called the exergetic cost, the amount of exergy per unit of time required to produce this flow, obtained by Eq. (4) where "A⁻¹" is the modified inverse matrix of the incidence matrix of the "A (m, n)", where A relates the flows with balances in equipment and propositions for their preparation, and the vector "Y*" for the external flow values applied to the system.

$$k = \frac{B^*}{B} \quad (3)$$

$$B^* = A^{-1}Y^* \quad (4)$$

With the incidence matrix "A (m, n)" and with the multiplication by the external cost vector "Z" we arrive at the costs "Π" thermoeconomic costs, shown by Eq. (5).

$$\Pi = A^{-1}Z \quad (5)$$

From these results, a comparison will be made of the costs of net electricity produced, the cost of live steam and process steam, as well as of the cooled air entering the compressor of the gas assembly, based on the fuel costs.

2.1 Evaporative cooling

These systems utilize the latent heat of water vaporization in an adiabatic air saturation process to reduce the dry bulb temperature to the wet bulb temperature. Highly dependent on the relative humidity of the environment air so that the process is successful in reducing the temperature, making it more suitable to hot and dry climates than hot and humid climates (Ameri and Hejazi, 2004).

It is considered the most cost-effective process for decreasing air temperature to increase the net power and efficiency of industrial gas cycles (Kim *et al.*, 2012). The evaporative cooling system receives warm, dry air entering from the left side, with flow to the right, then liquid water is then sprayed into small droplets, resulting in the evaporation of part of the water sprayed due to the absorption of heat from hot air. Consequently, causing a decrease in temperature and increase in the relative humidity of the air after the process (Çengel and Boles, 2013).

Figure 9 shows the reason why evaporative cooling is only indicated for hot and dry climates. The lower the relative humidity of the air to be cooled, the greater can be the cooling, since the maximum heat exchange occurs until the saturation of the air.

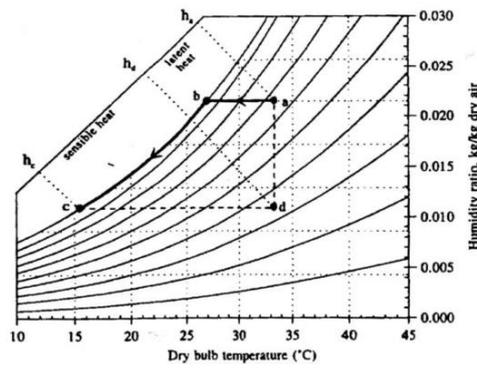


Figure 3. Air cooling process in psychrometric diagram (Ameri and Hejazi, 2004)

2.2 Absorption refrigeration system

This cooling process presents the circulation of binary solutions, being composed of a refrigerating fluid and an absorbent. It is studied the binary combination LiBr-H₂O, in which water will be the refrigerant. Based on Fig. 4, when the refrigerant vapor is coming from the evaporator, it will be absorbed into the liquid solution in the absorber (making the solution stronger) due to the higher concentration of coolant. This solution is pumped to high pressure into the heat exchanger, where the refrigerant will boil, making the solution weaker through the addition of heat.

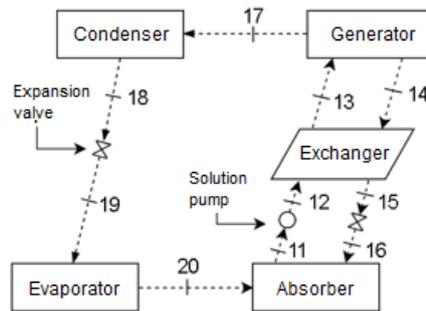


Figure 4. Absorption refrigeration scheme (adapted from Silva, 2015)

Subsequently, the refrigerant flows to the condenser, where it will reject heat and condense, after which it will suffer a drop in pressure and temperature as it passes through the expansion valve. In the evaporator, due to being at low pressure, the phase change will require a certain amount of heat, which will be removed from the environment, with this, will evaporate again and will join the weakest solution in the absorber, neglecting the refrigeration cycle, and after the supply of heat in the generator, the weaker liquid solution, due to the lower concentration of refrigerating fluid, will be destined for the absorber, going through an expansion valve, undergoing temperature and pressure drop, where it will join with the refrigerating fluid (Sençan, Yakut and Kalogirou, 2005).

The refrigeration process of Fig. 4 is called single-effect, since only one generator is used. There are currently systems with two and three generators, and are called, respectively, double- and triple-effect (Prasartkaew, 2014).

The heat from the cycle drive through the generator can be supplied from within the cycle itself or from external sources, and can be triggered by means of fuel combustion, gas exhaust gases or combustion engines, steam produced directly from boilers or from the output of gas turbines, and even hot water discarded from some process, among others.

2.3 Proposed combined cycle

Figure 3 illustrates the combined cycle to be analyzed. The configuration of the evaporative cooling unit at the gas compressor inlet (points 8 to 10) and the absorption refrigeration system (points 11 to 20), which will be used in isolation (Cases 1 and 2) and together (Case 3); points 31a and 32a relate to the activation of the ARS generator from the exhaust gases of the gas turbine; points 31b to 34b relate to the actuation of the ARS generator from the live steam of the recovery boiler; points 31c to 33c relate to the activation of the ARS generator from the steam turbine extraction steam (in the same thermodynamic state of the process).

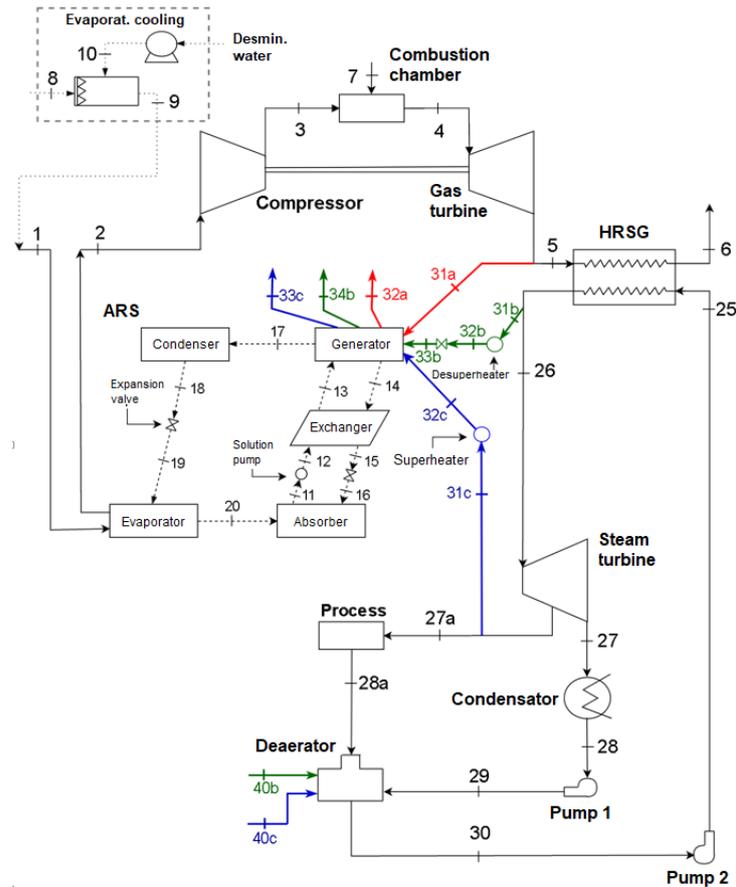


Figure 3. General conception of the combined cycle, contemplating all the technologies and routes of energy utilization (Adapted from Silva, 2015).

In the simulation, the same cross section of the inlet air duct of the cycle was used, together with a same velocity of the mass flow, resulting in a constant mass flow for all cases. The ambient condition was adopted at 25 ° C and 101,3 kPa.

The evaporative cooling will be responsible for the 20% reduction of the inlet temperature, and the absorption cooling system responsible for the 40% reduction of the inlet temperature.

3. PRELIMINAR RESULTS

By comparison with base case, parameters and values in Tab. 1, based in the first law analysis, Case 1 showed an increase in efficiency of de 2,57% using the same flow of fuel, demonstrate in Tab. 2, due to less compressor work. In Case 2, results in Tab. 3, the increase in yield is higher due to the higher capacity of refrigeration of ARS, resulting in addition around 7% in subcases a, b and c.

Table1. Case base without cooling

Parameters analyzed	Values
T ₂ - Temp. after cooling [°C]	-
Air flow [kg/s]	40,23
Compressor Work [kW]	16.238
Fuel flow[kg/s]	0,749
Heat provided [kW]	37.432
Net Work [kW]	15.451
Efficiency [%]	41,28

Table 2. Case 1 – Cooling with EC.

Parameters analyzed	Values
T ₂ - Temp. after cooling [°C]	20,0
Air flow [kg/s]	40,23
Compressor Work [kW]	16.029
Fuel flow [kg/s]	0,749
Heat provided [kW]	37.432
Net Work [kW]	16.411
Efficiency [%]	43,85

Table 3. Case 2– Cooling with ARS.

Parameters analyzed	Values		
	Case 2a	Case 2b	Case 2c
T ₂ - Temp. after cooling [°C]	17,5	17,5	17,5
Air flow [kg/s]	40,23	40,23	40,23
Compressor Work [kW]	15.760	15.760	15.760
Fuel flow [kg/s]	0,749	0,747	0,748
Heat provided [kW]	37.432	37.388	37.438
Net Work [kW]	18.042	18.048	18.165
Efficiency [%]	48,28	48,34	48,52

The results of Case 3 are demonstrate in Tab. 4, with an efficiency increase of around 6.5% compared to the base case, and a reduction in the compressor work of 135 kW compared to Case 2.

Table 4. Case 3 - Cooling with EC and ARS

Parameters analyzed	Values		
	Case 3a	Case 3b	Case 3c
T ₂ - Temp. after cooling [°C]	15,0	15,0	15,0
Air flow [kg/s]	40,23	40,23	40,23
Compressor Work [kW]	15.615	15.615	15.615
Fuel flow [kg/s]	0,748	0,738	0,744
Heat provided [kW]	37.404	36.932	37.170
Net Work [kW]	17.975	17.503	17.751
Efficiency[%]	48,06	47,39	47,76

4. CONCLUSIONS

Based in the first law of Thermodynamics, the effect of cooling the inlet air of the cycle can generate benefits in a combined cycle, using profitably the resources involved, due to the increased efficiency. The values reached are really interesting, and in accord to the literature, fact that incites a better investigation of the cooling process in gas power cycles and combined cycles, considering that Combined cycle is larger used around the World, using fossil fuels, and determined regions presents higher temperatures then 25 °C, where the cooling process became ever more attractive.

Considering the values obtained, the cooling using ARS proved to be of great value for the increase of the efficiency of the combined cycle, trough the fact that it is activated thermally by the own cycle, confirming its effectiveness. The Cases 2a and 3a shows great applicability, because it uses a part of the exhaust gases after de expansion in the gas turbine, through this, it is possible to produce more power from the energy used by the fuel, increasing its utilization, showing a possible solution in response to the increasing world energy demand.

It's necessary to know the better cooling process, requiring an exergetic analysis, considering the irreversibility generated by the second law of Thermodynamics, combined with a thermo-economic analysis, making possible a better vision of the cooling process cited in this research, also showing the less efficient components, where the tax of exergy destroyed is greater. From these results, a comparison will be made of the costs of net electrical energy produced, the cost of live steam and process steam, as well as of the cooled air entering the compressor of the gas assembly.

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