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Exergy analysis of a cogeneration power plant

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Abstract. *The exergy analysis of a cogenerative system which produces electricity through a gas turbine and superheated vapour was performed. The model is developed in order to produce 120 MW of electrical power while also investigating the exergy performance for each of the main components. In addition the exergy destruction and the exergy efficiency of the components is analysed in order to determine which ones present the larger potential for improvements*

Keywords: *Exergy analysis, cogenerative system, exergetic efficiency.*

INTRODUCTION

Energy production has become an increasingly important subject given the substantial increase in energy demand. This large increase occurs mainly due to the population growth and entails in a need for more efficient methods for energy generation. To analyze and optimize the efficiency of different types of plants, it is important to identify the components with the highest irreversibilities. To perform such study and try to minimize these inefficiencies, a very useful thermodynamic tool is utilized which is the concept of exergy analysis.

Exergy is a thermodynamic property which indicates the maximum amount of work that can be extracted from a system or control volume until it comes in a state of equilibrium with the environment. Unlike energy, exergy is conserved only during ideal processes and destroyed due to irreversibilities in real processes, which cause the efficiency of the process or component to drop and must be minimized (Rosen and Scott, 2003). It is known that exergy analysis leads to a better understanding of the influence of thermodynamic phenomena on the process effectiveness, comparison of the importance of different thermodynamic factors, and the determination of the most effective ways of improving the process under consideration (Sengupta, *et al*, 2006). Aiming to improve the efficiency of power plants, several researchers utilized this tool on their work for several different types of plants such as thermoelectric (Ameri, *et al*, 2008; Baghernejad and Yaghoubi, 2011), combined cycle (Kamate and Gangavati, 2009; Bejan and Tsatsaronis, 1996), cogeneration (Lazzaretto and Tsatsaronis, 2006; Balli, *et al*, 2008) and even geothermal power plants (Mohammadkhani, *et al*, 2013).

1. EXPERIMENTAL PROCEDURE

The plant contains two turbines producing 120 MW of electricity, each one with natural gas as fuel. It also produces superheated vapor at 368.7 °C and 10.44 MPa with a mass flow rate of 69,3 kg/s using exhaust combustion gases leaving at 129,2 °C with a mass flow rate of 359 kg/s. In the study, numerical data are based on site measurements with ambient temperature of 31 °C and ambient pressure of 100 kPa at Northeast of Brazil. Fig. 1 shows a schematic diagram of a cogeneration power plant which produces both electricity and steam.

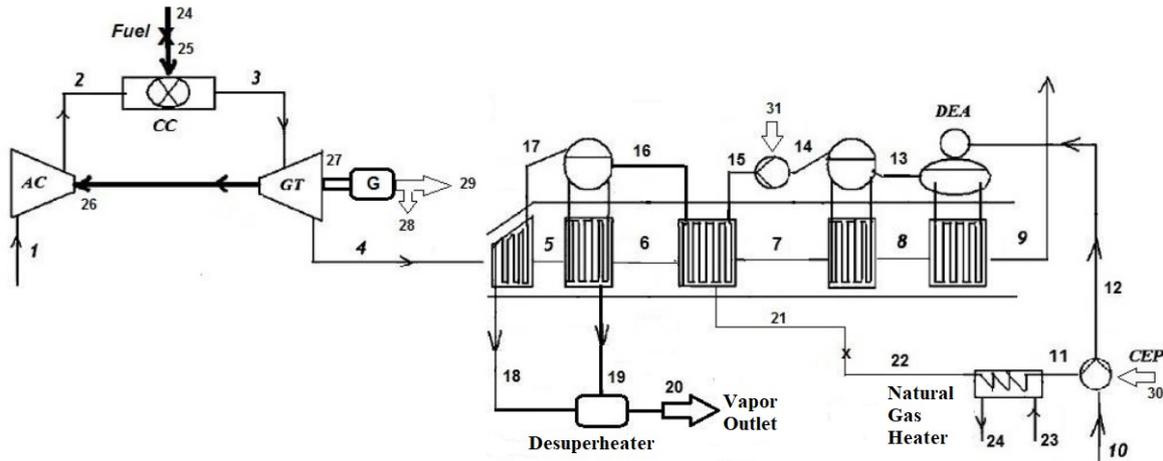


Figure 1 – Schematic diagram of cogeneration plant.

For the exergy balance, a few assumptions were made to apply the mathematical model to the system, such as:

- The system is considered to be in steady state
- The reference environmental state for the system is defined by the environment temperature (T_0) of 31 °C
- When there is no data, the pressure drops in all pipelines and heat exchangers are considered to be negligible
- The combustion chamber efficiency is considered as 98%
- The electric generator efficiency is assumed as 98%
- All heat exchangers were considered adiabatic

Table 1 shows the natural gas composition. The composition of the natural gas and its properties are important in combustion model. The combustion was determined according to the first law of thermodynamics for reaction systems at steady state. The natural gas composition and its low heat value (LHV) are shown in table 1.

Table 1. Composition and Typical Properties of Natural Gas.

Component	Volume (%)	Mass (%)	LHV (MJ/kg)
Methane	88.82	80.32	50.000
Ethane	8.41	14.26	47.525
Propane	0.55	1.37	46.390
Nitrogen	1.62	2.56	-
Carbon dioxide	0.60	1.49	-
Total	100.00	100.00	47.574

The performance of the gas turbine is evaluated by the manufacturer in the standard condition (15 °C, 101.3 kPa, RH 60%), however, in hot regions, this performance is decreased. Real data of gas turbine performance for this study was investigated by (Cavalcanti and Silva, 2013). In the ISO conditions, the nominal net power is 171 MW, the air mass flow is 445 kg/s and the pressure ratio is 16:1. As the ambient temperature is higher than the ISO condition, the mass flow rate of air and pressure ratio are reduced. The effect of air temperature on the mass flow rate of air, pressure ratio and electric power were estimated by equations below, according to the data of (Cavalcanti and Silva, 2013; Cavalcanti, 2017). They are based on the ISO conditions above.

$$r(\%) = \frac{r_p}{16} = 127.94 - 1.8596 T_{amb} (^\circ C) \quad (1)$$

$$\dot{m}_{air}(\%) = \frac{\dot{m}}{445} = 120.32 - 1.2824 T_{amb} (^\circ C) \quad (2)$$

$$\dot{W}_{elec}(\%) = \frac{\dot{W}}{171} = -0.0008 T_{amb}^2 (^\circ C) + 0.0198 T_{amb} (^\circ C) + 0.8815 \quad (3)$$

1.1 Exergy analysis

The mass, energy and exergy balance were carried out for each component. There are different approaches for exergy balance and exergy efficiencies in the literature. This research used the specific exergy costing (SPECOC) approach which uses the fuels and products definition. This method deals with the fuel and product definitions that also consider the components of exergy (mechanical, thermal and chemical) (Lazzaretto and Tsatsaronis, 2006). The product E_p and the fuel E_f are defined considering the desired result produced by the component and the resources expended to generate this result. The product is defined to be equal to the sum of all the exergy values to be considered at the outlet plus all the exergy increases between inlet and outlet that are in accord with the purpose of the component. The fuel is defined to be equal to all the exergy values to be considered at the inlet plus all the exergy decreases between inlet and outlet minus all the exergy increases that are not in accord with the purpose of the component. The exergy balances, the exergy destruction and the exergetic efficiency for each component were evaluated.

2. RESULTS AND DISCUSSION

The exergy analysis is performed according to the model previously described. Table 2 shows the general thermodynamic parameters used and calculated in the numerical simulation. It is possible to observe the exergy, mass flow rate and temperature of the vapor at the exit, thus being able to analyze such variables.

Table 2. Performance parameters in each point

	\dot{m} [kg/s]	T [°C]	P [kPa]	Ex [kW]
1	351.2	31.0	101	0
2	351.2	390.0	1079	118654
3	359.0	1206.0	1025	384460
4	359.0	621.0	101	114337
5	359.0	520.2	101	86856
6	359.0	354.1	101	47687
7	359.0	214.5	101	22601
8	359.0	158.9	101	15304
9	359.0	129.3	101	12214
10	69.3	45.0	10	3546
11	3.1	31.0	10	153
12	72.4	44.5	2136	3851
13	72.4	82.2	2136	4937
14	72.4	152.8	513	9583
15	72.4	155.4	12910	10674
16	69.3	304.9	12050	29469
17	50.9	315.4	10640	54613
18	50.9	575.2	10640	78688
19	18.4	307.6	10640	7971
20	69.3	368.7	10440	83588
21	3.1	348.5	12050	3528
22	3.1	237.6	2635	3002
23	7.8	-88.8	4638	405022
24	7.8	165.9	3266	389700
25	7.8	165.9	2716	389495
26				124430
27				122550
28				1137
29				118960
30				155
31				982

The exergy analysis of a cogeneration system with electricity and steam as products were carried out according to the model described by (Bejan and Tsatsaronis, 1996).

The performances of the air compressor and gas turbine were based on real data of work as shown in (Cavalcanti and Silva, 2013). The equations for the isentropic efficiency of the air compressor and gas turbine were developed based on the pressure ratios.

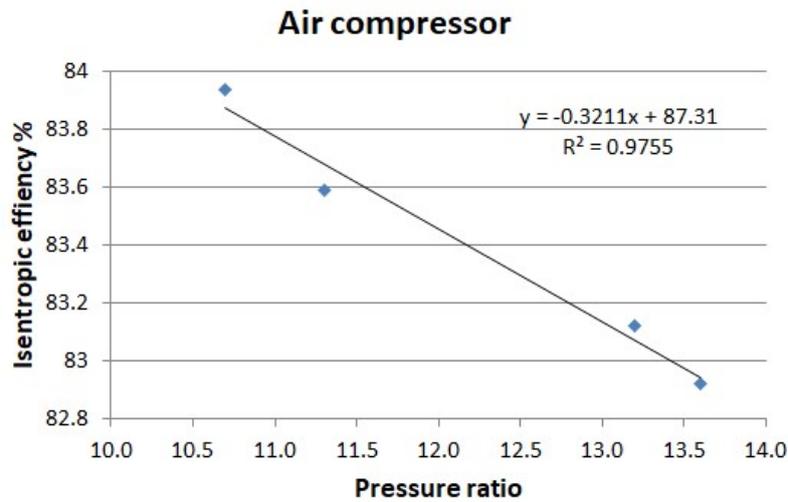


Figure 2 - Isentropic efficiency of the air compressor based on the pressure ratio.

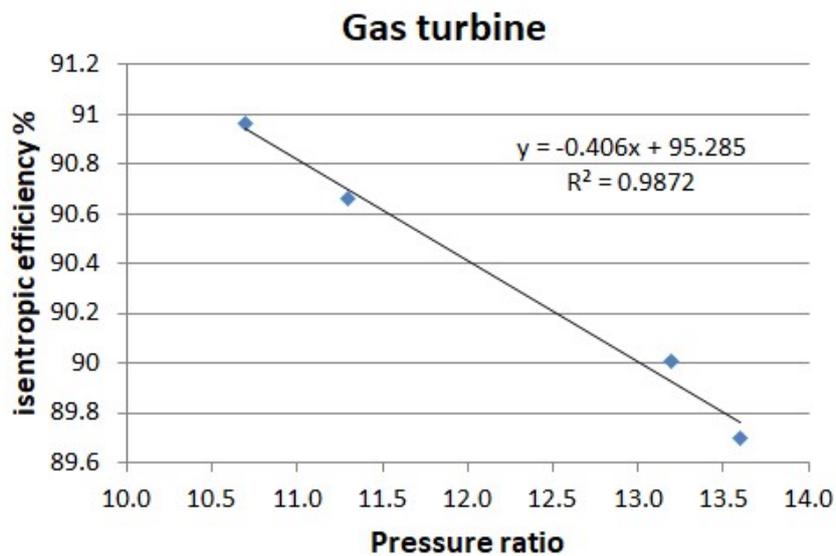


Figure 3 - Isentropic efficiency of the gas turbine based on the pressure ratio.

As the pressure ratio increases, both isentropic efficiencies of the air compressor and gas turbine reduces. This performance is described in the literature by (Cavalcanti and Silva, 2013).

The model of the cogeneration plant was developed through the application of real data. The first law of thermodynamics was applied including the combustion chamber and turbine, also evaluating the total heat transfer in both components. The heat transfer at the combustion chamber was assumed as 2% and constant, however at both components, its value is not constant. The ratio of total heat transfer at the combustion chamber and turbine by the total turbine power was evaluated. The effect of air temperature on the heat transfer ratio by the turbine power is shown.

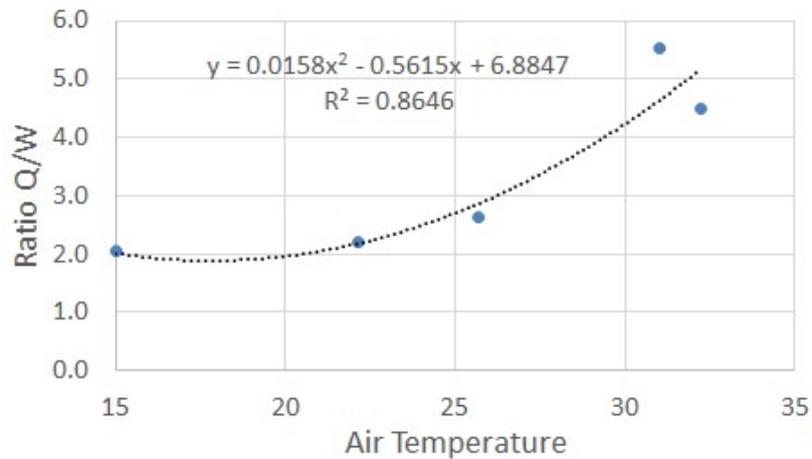


Figure 4 - Ratio of total heat transfer at the combustion chamber and turbine by power turbine versus air temperature.

The total heat transfer ratio at the combustion chamber and turbine by power turbine increases as air temperature increases. The power of the turbine decreases as the air temperature increases according to equation (3). Therefore, the total heat transfer ratio at the combustion chamber and turbine by power turbine is reduced. The validation of the empirical model was performed through the calculation of the error in the exergetic efficiency. Its values between the experimental data and empirical model changed from -3.6% at 15 °C to 6.0% at 32.31 °C.

When the air temperature increases, the mass flow rate of air is smaller, thus producing less electrical power according to equations (2) and (3). The performance of gas turbines is worse when they are used in a location with hot weather resulting in a reduction of output power (Khaliq and Dincer, 2011). Other researchers have discussed the effect of air environmental temperature on the reduction of electrical power and air mass flow rate in gas turbine systems such as (Cavalcanti and Silva, 2013; Cavalcanti, 2017). Nonetheless, as air temperature increases, the fuel consumption decreases to control the maximum exhaust gases temperature requirement. The fuel consumption is important to evaluate the cost rate and environmental impact of the system. However, the reduction of fuel consumption is lower than the power output reduction. Real data of gas turbines (Cavalcanti and Silva, 2013; Cavalcanti, 2017) shows that increasing air temperature from 22.15 °C to 32.2 °C, the output power and fuel consumption reduces from 155.5 MW to 119.1 MW (23.4%) and 9.28 kg/s to 7.72 kg/s (16.8%), respectively. Therefore, the increase of air temperature reduces more the output power than the fuel consumption. The performance of the global exergetic efficiency with air temperature can confirm this fact. Fig 5 shows the variation of global exergetic efficiency with air temperature.

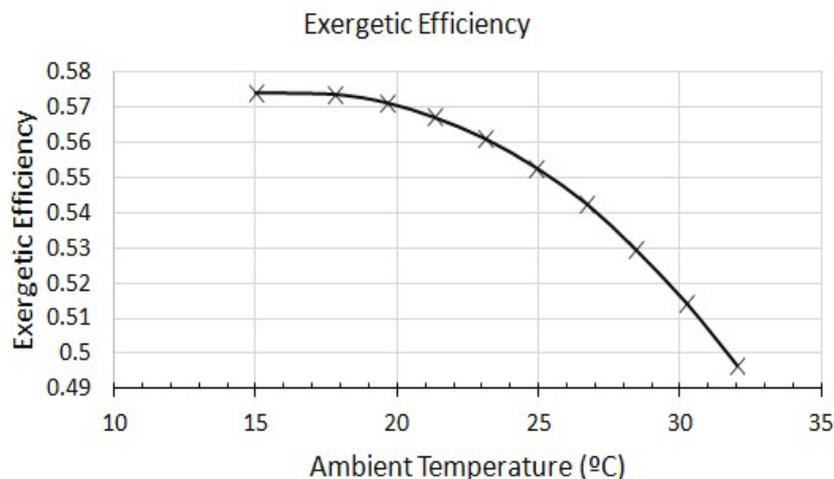


Figure 5 - Effect of air environmental temperature on global exergetic efficiency.

As air environmental temperature increases, the global exergetic efficiency reduces. This happens due to the accentuated reduction in the exergy rate of steam and electricity when compared to the reduction in the fuel consumption.

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