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THERMODYNAMIC ANALYSIS OF A TRIGENERATION SYSTEM FOR A RESORT

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Abstract. *The present work aims to study the maximum use of energy for a resort in Brazilian northeast. A trigeneration system was proposed to supply the thermal load, the hot water demand for the bathrooms and the kitchen, and the electrical energy demand. The resort has an electrical generator of 240 kVA and has a thermal load of 288 kW. The heat rejected by the exhaust gases from the diesel engine has been used in a double effect absorption chiller and the cooling water from the engine jacket has been used in a single effect absorption chiller, both with water-lithium bromide. The energy analysis was developed to define heat and mass transfers and the Coefficient of Performance (COP). As the First Law of Thermodynamics is not enough to analyze the system, the exergy analysis is applied to determine the exergy destroyed and the Second Law efficiency of each component. The proposed system supplies 90% of the actual thermal load of the resort and provides 127,68 kW of heat for hot water. The high pressure generator presents the greater destroyed exergy and the single effect generator has the best exergy efficiency. The proposed system has attended well to the thermal requirements of the resort.*

Keywords: *absorption chiller, energy analysis, exergy analysis, trigeneration*

1. INTRODUCTION

Currently, energy is essential for daily life, mainly due to economic growth and technological development. A high electrical energy demand results in environmental problems since great part of the energy comes from fossil fuels that emit greenhouse gas (Mohammadi *et al*, 2017). Therefore, solar and wind energy or the efficient use of fossil fuels can be considered an excellent strategy to mitigate this problem. (Khatri and Singh, 2017).

Trigeneration systems are an option of great efficiency since the energy rejected by a process is utilized for other applications (Espirito Santo, 2012). Trigeneration is defined as the generation of three forms of energy from a primary energy source (Balli, *et al*, 2010), such as gas turbines, fuel cells, steam turbines and internal combustion engines which it was used in this work.

Electricity, cooling and heat are the forms of energy produced by the trigeneration system (Chitsaz *et al*, 2015). In this study, the electricity is produced by an electrical generator coupled to an internal combustion engine. The waste heat is used to move an absorption refrigeration system, an alternative type of air conditioning technology (Farshi *et al*, 2013).

For a resort, to reduce the electrical power costs and increase the efficiency of the systems are primary issues. Considering this, a system was proposed to maximize the efficiency of the use of electric and thermal energy of the resort through the trigeneration, using the electric generator as primary energy, two absorption systems for the air conditioning and heat exchangers for hot water.

The First and the Second Law of Thermodynamics are used to analyze the trigeneration system proposed. The First law provides a quantative analysis of the system, showing the COP, the heat transfers rate and the power input. In the other hand, the Second law gives a qualitative analysis, evaluating the exergy losses due to the irreversibilities, the exergetic efficiency (Gogoi and Talukdar, 2014). In this context, to ensure the best use of the available energy sources, this study aimed to carry out an energy and exergy analysis for a trigeneration system using a diesel engine.

2. SYSTEM DESCRIPTION

The system consists of an electrical generator coupled to an internal combustion engine. The exhaust gases from this engine were used three times. First, the exhaust gases provide heat to the high-pressure steam generator of the double effect absorption chiller. Then, these gases, at a lower temperature, exchange heat with the cooling water of the engine. Subsequently, the gases leave for a heat exchanger, in which the heating of water for domestic use occurs (Fig. 1). Thereby, there is a maximum utilization of the energy of the exhaust gases, making use of the available heat in three levels of temperature.

The cooling water of the engine is used twice. After being warmed by the exhaust gases, the cooling water plus an amount of recirculating water is routed to provide heat to the steam generator of the single effect absorption chiller. Thereafter, this water is directed to a heat exchanger to warm water for domestic use at a lower temperature level than in the first heat exchanger.

Accordingly, the maximum of the energy that would be wasted is used to provide heat and cooling. The double effect and the single effect absorptions chillers ensuring great part of the thermal load required by the resort. The heat exchangers to warm the water intended to supply the needs that the resort has for domestic use in two levels of temperature. This is important because, in the kitchen, for cooking and for sterilizing utensils requires hot water at a higher temperature than that required for the showers in the guest bathrooms.

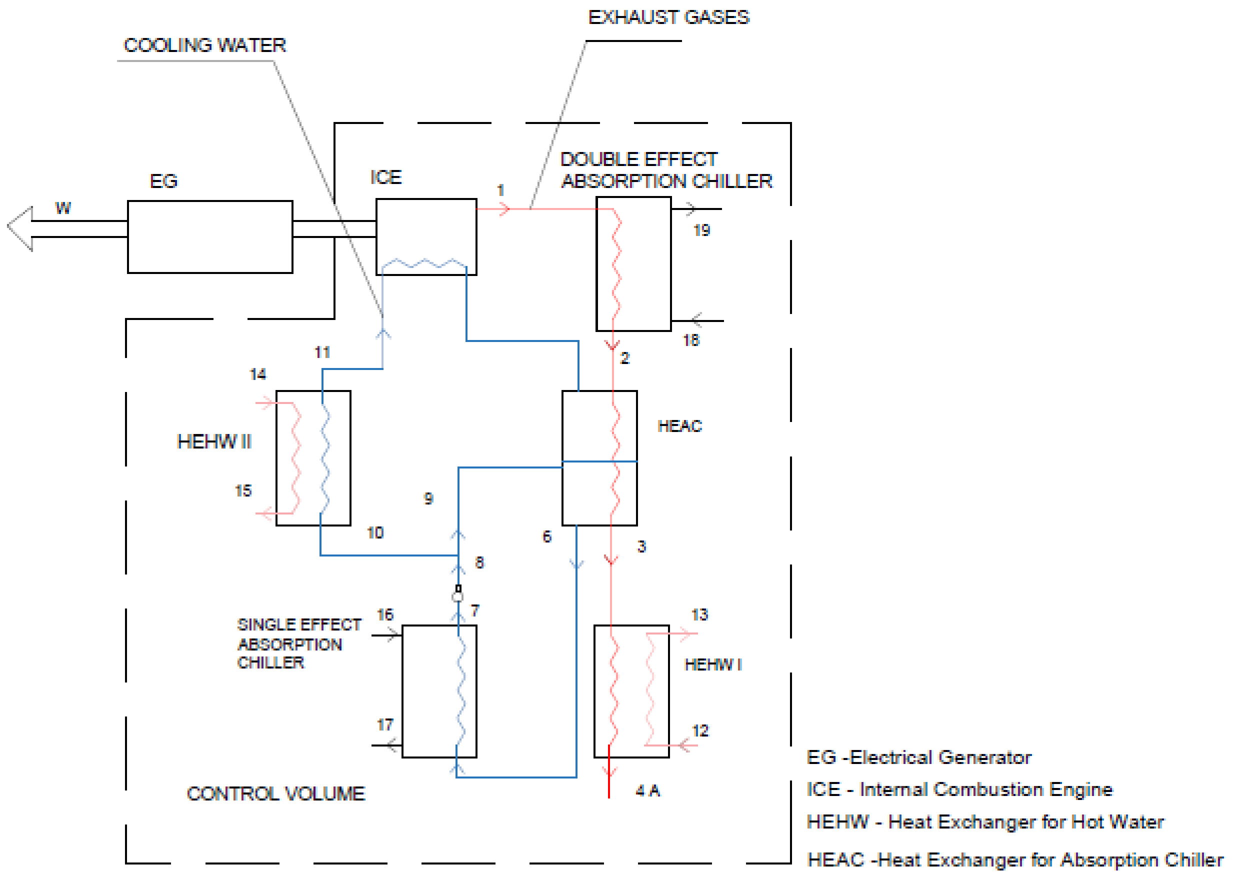


Figure 1. Trigeneration system proposed for the resort in study.

Both absorption chillers work with water as refrigerant and lithium bromide as absorbent. The resort under study has an electrical generator of 240 kVA coupled with a diesel engine. The resort thermal load is currently supplied by splits systems, with a cooling capacity of 288 kW.

The proposal of this study is to replace these splits by a chilled water system without mechanical compression. The absorption chillers are ideal for this because they do not get the cooling effect by mechanical compression, but through a desorption process (when water vapor separates from lithium bromide), which only requires a heat source. In the trigeneration system of the study, the heat source is the energy recovered by the exhaust gases for the double effect chiller and the energy recovered by the cooling water from the engine jacket to the single effect chiller. According to Shelar *et al* (2016), a trigeneration system with two chillers using two sources of heat is more efficient than a system with only one.

The difference between a double effect and a single effect chiller is desorption. In the double-effect chiller, this desorption is made in two generators (high and low pressure). On the other hand, in the single effect chiller, this desorption is made in only one generator. In this work, only the input and output heat streams of the chillers were studied.

3. THERMODYNAMIC ANALYSIS

For the thermodynamic analysis of the proposed system, the First and the Second Law were applied to each component in the control volume. To simplify the analysis, the following assumptions are considered:

1. The system operates in steady state conditions.
2. Kinect and potential energy are negligible.
3. The heat loss from the equipment to the environment are negligible.
4. Pump has constant isentropic efficiency.
5. The refrigerant is considered pure water.
6. The pressure drops by friction in the piping and in the heat exchangers are negligible.

3.1 Energy analysis

In order to simulate the trigeneration systems, the equations of mass and energy conservation were applied. Equation (1) shows the mass balance:

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \tag{1}$$

Here $\dot{m}$ denotes the mass flow rate. The energy balances for the main components of the control volume is in the equations below:

$$\dot{Q}_{2,3}=\dot{m}_2*C_{p,eg}*(T_2-T_3)=\dot{m}_6*h_6-\dot{m}_5*h_5-\dot{m}_9*h_9 \tag{2}$$

$$\dot{Q}_{3,4}=\dot{m}_3*C_{p,eg}*(T_3-T_4)=\dot{m}_{12}*C_{p,w}*(T_{13}-T_{12}) \tag{3}$$

$$\dot{Q}_{10,11}=\dot{m}_{10}*C_{p,w}*(T_{10}-T_{11})=\dot{m}_{14}*C_{p,w}*(T_{15}-T_{14}) \tag{4}$$

$$\dot{Q}_{1,2}=\dot{m}_1*C_{p,eg}*(T_1-T_2) \tag{5}$$

$$\dot{Q}_{6,7}=\dot{m}_7*C_{p,w}*(T_6-T_7) \tag{6}$$

$$COP=\frac{\dot{Q}_{evap}}{\dot{Q}_{ger}} \tag{7}$$

Where $\dot{Q}$ is the heat transfer rate, h is the enthalpy, T the temperature, C_p the specific heat of the stream and *COP* is the coefficient of performance of absorption chiller. The numerical subscripts are related to Fig.1. The subscript w is for water and eg for exhaust gases.

3.2 Exergy analysis

While the first law defines the amount of energy and mass in the system, the second law determines the quality of the system through exergy. This property can be set as the maximum work that could be obtained from a system at a specified state (Ahmadi *et al*, 2012). The exergy is composed of four components: physical, chemical, kinect and potential. In this work, the physical (ex_{ph}) and chemical (ex_{ch}) exergy was considered meanwhile the changes in elevation and speed are negligible.

$$ex_{ph}=(h-h_0)-T_0*(s-s_0) \tag{8}$$

$$ex_{ch}=\frac{1}{M}[\sum_i (y_i*\bar{\varepsilon}_i)+R*T_0*\sum_i (y_i*ln\,y_i)] \tag{9}$$

$$ex_{tot}=ex_{ph}+ex_{ch} \tag{10}$$

$$I=\sum_{in} \dot{m}*ex_{tot}-\sum_{out} \dot{m}*ex_{tot} \tag{11}$$

$$\eta = \frac{\Delta ex_{tot,p} * \dot{m}_p}{\Delta ex_{tot,i} * \dot{m}_i} \tag{12}$$

Where s is the entropy, M the molecular mass, y is the mole fraction, $\bar{\varepsilon}$ the standard chemical exergy, $\bar{R}$ the universal constant of gases, I the exergy destroyed and η the exergy efficiency.

3.3 Input parameters

Several input parameters were necessary to start the simulation (Tab.1). Temperatures were based on absorption chillers catalogs from a reference manufacturer. The mass flow rates were calculated based on the data from the internal combustion engine of the hotel under study.

Table 1. Input data for the trigeneration system in study.

Parameter	**Value**
Exhaust gases inlet temperature in the double effect absorption chiller	530 ºC
Exhaust gases outlet temperature in the double effect absorption chiller	200 ºC
Mass flow of exhaust gases from the internal combustion engine	0,318 kg/s
Mass flow of cooling water from the internal combustion engine	5,09 kg/s
Hot water inlet temperature in the single effect absorption chiller	90,6 ºC
Hot water outlet temperature in the single effect absorption chiller	85 ºC
COP of double effect absorption chiller	1,3
COP of single effect absorption chiller	0,7

4. RESULTS AND DISCUSSIONS

The main properties of the trigeneration system proposed were calculated by EES (Engineering Equation Solver) software. Temperature, mass flow, enthalpy and entropy were obtained by the energy analysis and the exergy by the Second Law analysis.

Table 2. Thermodynamic Properties of state points in Fig.1.

Point	$\dot{m}$ *(kg/s)*	*T* *(ºC)*	*h* *(kJ/kg)*	*s* *(kJ/kg.K)*	ex_{ph} *(kJ/kg)*	ex_{ch} *(kJ/kg)*	ex_{tot} *(kJ/kg)*	Ex_{tot} *(kW)*
1	0,318	530	595,3	1,087	271,3	47,36	318,7	101,3
2	0,318	200	198,8	0,4905	52,55	47,36	99,91	31,77
3	0,318	120	106,9	0,2913	20	47,36	67,36	21,42
4	0,318	65	44,69	0,1317	5,417	47,36	52,78	16,78
5	5,09	90	377,2	1,193	26,11	49,96	76,07	387,2
6	5,847	90,6	379,7	1,2	26,56	49,96	76,52	447,4
7	5,847	85	356,2	1,135	22,44	49,96	72,4	423,4
8	5,847	85	356,2	1,135	22,44	49,96	72,4	423,4
9	0,7573	85	356,2	1,135	22,44	49,96	72,4	54,83
10	5,09	85	356,2	1,135	22,44	49,96	72,4	368,5
11	5,09	80	335,2	1,076	19,03	49,96	68,99	351,2
12	0,1437	25	105,1	0,3682	-0,09826	49,96	49,86	7,166
13	0,1437	60	251,5	0,8321	7,995	49,96	57,96	8,329
14	1,697	25	105,1	0,3682	-0,09826	49,96	49,86	84,6
15	1,697	40	167,9	0,5734	1,481	49,96	51,44	87,28
16	4,172	12,2	51,3	0,1837	1,052	49,96	51,01	212,8
17	4,172	6,7	28,26	0,1022	2,306	49,96	52,27	218,1
18	7,857	12	50,65	401,2	1,108	49,96	51,07	0,1814
19	7,857	7	29,71	410,2	2,251	49,96	52,21	0,1074

Table 3 reveals the energy balance of the trigeneration system proposed. As the control volume has no significant work value, only the heat transfer rates are shown.

Table 3. Energetic analysis of the trigeneration proposed system.

Energy Balance	
Heat Transfer Rate	(kW)
High pressure generator	126,5
Single effect generator	137,2
Heat exchanger for single effect absorption chiller	30,66
Heat exchanger for hot water I	21,08
Heat exchanger for hot water II	106,6
Chilled water from the double effect chiller	164,4
Chilled water from the single effect chiller	96,04

The heat transfer for chilled water is calculated by the *COPs* given in Tab.1. Thereby, the thermal load totalizes in 260,44 kW. The heat for warm the water for domestic uses is 127,66 kW, available in two levels of temperature. This is important because it allows the hotel to use hot water for two different functions. Table 4 and Table 5 presents the exergy destroyed and the exergy efficiency, respectively.

Table 4. Exergy destroyed of the main components of the proposed system.

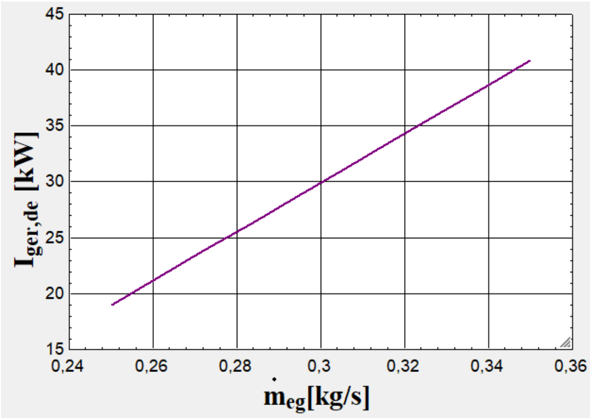
Exergy destroyed	(kW)
High pressure generator	33,26
Single effect generator	2,25
Heat exchanger for single effect absorption chiller	4,91
Heat exchanger for hot water I	3,48
Heat exchanger for hot water II	14,69

The generator of the double effect chiller has the higher exergy destruction. The generator of single effect chiller has the higher exergy efficiency.

Table 5. Exergy efficiency of the main components of the proposed system.

Exergy efficiency	(%)
High pressure generator	51,32
Single effect generator	90,66
Heat exchanger for single effect absorption chiller	52,56
Heat exchanger for hot water I	25,07
Heat exchanger for hot water II	15,42

The energetic and exergetic performance of double effect chiller and of the single effect chiller are evaluated. The variation of exergy destroyed in the generator of both chillers and their thermal load were analyzed in relation to the increase of the exhaust gas mass for the double effect chiller and the engine jacket cooling water for the single effect chiller. This mass variation represents the change in diesel engine load.



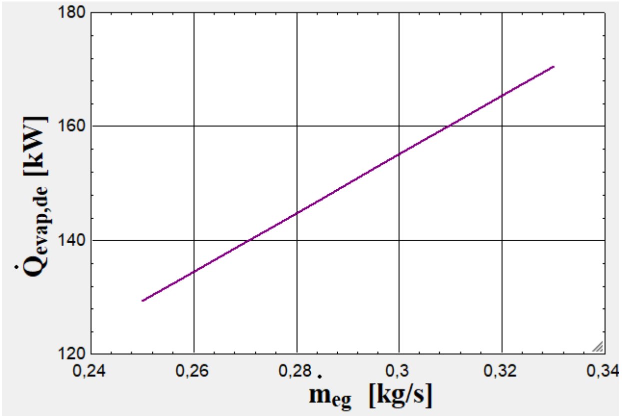
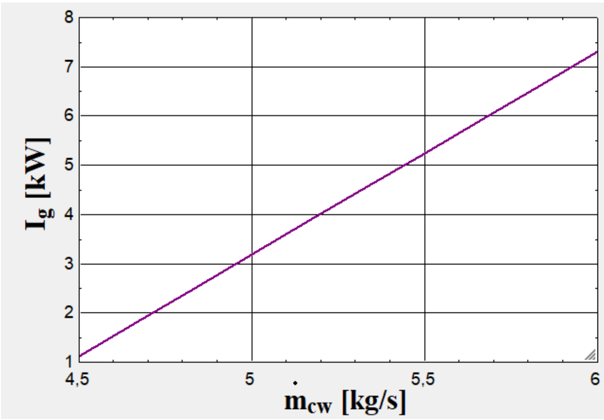


Figure 2. Relation between irreversibility of the generator and the mass of exhaust gases for double effect chiller.
Figure 3. Relation between thermal load and the mass of exhaust gases for double effect chiller.



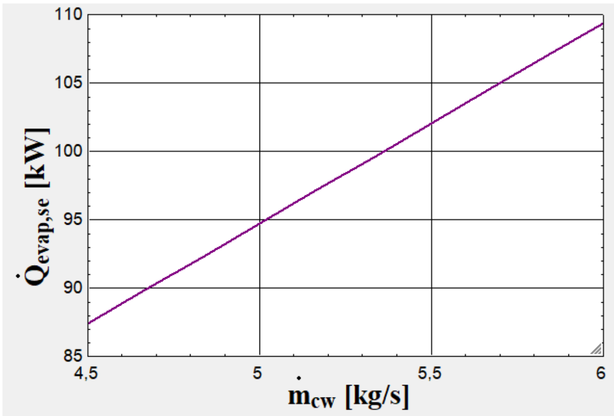


Figure 4. Relation between irreversibility of the generator and the mass of cooling water for single effect chiller.
Figure 5. Relation between thermal load and the mass of cooling water for single effect chiller.

The same relation was observed for both chillers. The higher the mass, the greater is the load and the irreversibility. However, there is also an increase in the thermal load available. This means that if the system does not operate at full load, it will have a better exergetic performance.

5. CONCLUSION

In this study, the First and the Second Law of Thermodynamics have been applied to a trigeneration system proposed for a resort. From a diesel engine of an electrical generator of 240 kVA, with the recovered energy of the exhaust gases and the cooling water of the engine jacket, it was possible to obtain a system with 260,44 kW of thermal load. 164,4 kW of a double effect chiller and 96,04 kW from a single effect chiller. This corresponds to 90% of the resort's thermal load. This is very satisfactory, since it is rare for the resort to require 100% of the thermal load installed.

For hot water heating, 127,68 kW of heat was obtained, at two temperature levels, for use in kitchens and bathrooms.

In relation to the exergetic performance, the double effect generator presented the highest amount of destroyed exergy. This occurs because of the large temperature difference between the exhaust gases and the working fluid in the generator. However, this component still has a good exergetic efficiency.

The proposed trigeneration system corresponded with good energy and exergetic results for the needs of the resort in study. For future works, it is interesting to carry out an economic study to analyze the feasibility of the proposed system.

6. ACKNOWLEDGEMENTS

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