EXERGY ANALYSIS OF A TRIGENERATION SYSTEM POWERED BY SOLAR ENERGY USING FRESNEL CSP TECNOLOGY

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Abstract. *In this work it was implemented an Exergy analysis to verify the performance of a trigeneration system that consist of a heat exchanger to provide 1600 kW of heating, a cooling system using an absorption chiller that provide 800kW of refrigeration and a Rankine cycle to produce 500 kW of electricity. Solar radiation is absorbed using Fresnel CSP technology and it is the source of the energy for the proposed trigeneration system. The exergy analysis is made by vivificating the exergy destruction of each of main equipment and through the exergetic efficiency of the entire cycle as well. It can be seen that the largest sources of exergy destruction of the proposed system occurred in the solar collector, followed by the generator of the refrigeration system and the turbine, respectively. In addition to the equipments' analysis, it was investigated the influence of four different types of fluids (Water, R123, Novec649 and N-octane) in the Rankine cycle in the exergetic system performance. It was noticed that the fluid that provide the best exergetic efficiency in the cycle was Water followed by N-Octane.*

Keywords*: Trigeneration, Exergetic Analysis, Fresnel, CSP*

1. NOMENCLATURE

Latin

A	Total collector aperture Area	$\dot{Q}$	Heat transfer rate
h	Enthalpy	T	Temperature
I	Irradiation	x	Mass fraction
$\dot{m}$	Mass flow	$\dot{W}$	Power rating
P	Pressure		

Geek symbols

Ψ	Exergy
η	Efficiecy

Subscript

0	Environment	i	In
$1-15$	Respective system points	II	Second law
abs	Absorber	net	Net
$coll$	Collectors	o	Out
$cond$	Condenser	p	Pump
$dest$	Destruction	s	Surface
ger	Generator	tot	Total
h	Heat system		

2. INTRODUCTION

With the increase of the environment concern around the human activity and nature preservation, the search for more efficient and less polluting processes guide researches and studies in several areas, such as the generation of electricity. Concomitantly, the dependence on fossil fuels for energy production in various countries corroborates the research of renewable and sustainable energy sources. With these justifications trigeneration emerged as a possible energy recovery solution, as it significantly increases the efficiency of a system, reducing environmental impacts and reducing costs (Al-Sulaiman, 2010).

The Fresnel technology has one economic advantage between the others Concentrated Solar Power technologies like Parabolic Trough Collectors (PTC) due the use of flat mirrors and structural advantages (Morin, 2012). A trigeneration organic Rankine cycle used by Guimarães et al. (2016) has an intermediate heat exchange to pass the heat from water, which is the solar field fluid, to the organic fluid n-octane in the power-block system. There is high exergy destruction with this process that could be eliminated with the direct integration of the solar field with the power-block using water as working fluid and Fresnel for the solar field. With Fresnel technology, it is possible to handle high vapor pressures because it has no rotating parts as PTC.

The Fresnel is a concentrating solar power (CSP) technology. Its stables mirrors concentrate the sunlight on a pipe above the them, the absorber. With linear receivers and reflectors, which are segmented in single axis tracking heliostats. The reflector mirrors are aligned to track the sun without need of movement at all. According to Abbas et al. (2012), Fresnel colllectors can provide high temperatures as 550°C.

In the trigeneration the thermal efficiency can reach almost 80%, better than the efficiency of each process alone, heating, cooling and power production. Conventional plants that only generate electricity have a thermal efficiency about 40%, while the overall efficiency of plants called combined power cycle or cogeneration that produce electricity and heat is around 60% (Al-Sulaiman, 2010). With solar energy development, small to medium buildings like resorts are looking for trigeneration due to the sustainability proposal and the reduced pay-back achieved by new technologies. Buonomano et al. (2014) presented a model for simulation and optimization of a small trigeneration plant supplied by solar and geothermal energy. This work also made a case study in which a system was developed for application in a hotel located in southern Italy; Ischia, where a micro trigeneration plant modeled previously was tested. The system has high rates of efficiency and economic return in the worst case of 7.6 years and 2.5 years for the scenario considered convenient.

Several performance studies on Rankine working fluids are being made nowadays. Mavrou et al. (2015) assesses the impact of heat source variability for different working fluid mixtures studying parameters such thermal efficiency, net generated power, volume ratio across the turbine, the mass flow rate of the working fluid and the required collector aperture area for each fluid. The use of water, n-octane, R123 and Novec649 fluids are evaluate in this paper for the proposed trigeneration system.

In the Brazilian context solar energy presents itself as one major energy source for research and development, since the irradiance in the territory is considerably higher than those of European countries, such as Germany and France. This paper presents a model of trigeneration with use of solar energy and makes a comparative study of the influence of each working fluid in the exergy efficiency and aperture area needed for the solar field.

3. METHODOLOGY

The methodology used in this study contains the description of the trigeneration system, model presentation and components.

3.1 System description

The trigeneration system investigated in this paper is shown in Fig. 1, consisting of a Rankine power cycle, that use Fresnel collectors as their heat source, the trigeneration system contains an absorption refrigeration system using ammonia-water as a working fluid and a heating system. Both the heating and refrigeration systems use the heat lost by the Rankine cycle to power themselves.

3.2 Description of the model developed

In this paper we used the Engineering Equation Solver Platform (EES) to simulate the trigeneration system shown in Fig. 1. The system model considered an electrical output power of 500 kW, 1600kW as heating heat and 800 kW as cooling power. The followed assumption was made in order to simplify the model:

- It was disregarded heat losses to environment in pipes and equipment;
- It was disregarded pressure drop in all the heat exchangers presents in the system: Heating system, Generator, Evaporator, Condenser, Absorber and refrigeration Heat Exchanger
- It was assumed 20% of pressure drop in the Fresnel collectors.

The parameters and input variables in the simulation are presented in Tab. 1, considering the basic settings for this job. The model consists of performing energy balance, exergy and mass on all system components.

3.2.1 Energy analysis

The energy analysis was used to determine the output variables of the equipment and system taking into account the input variables shown in Tab. 1.

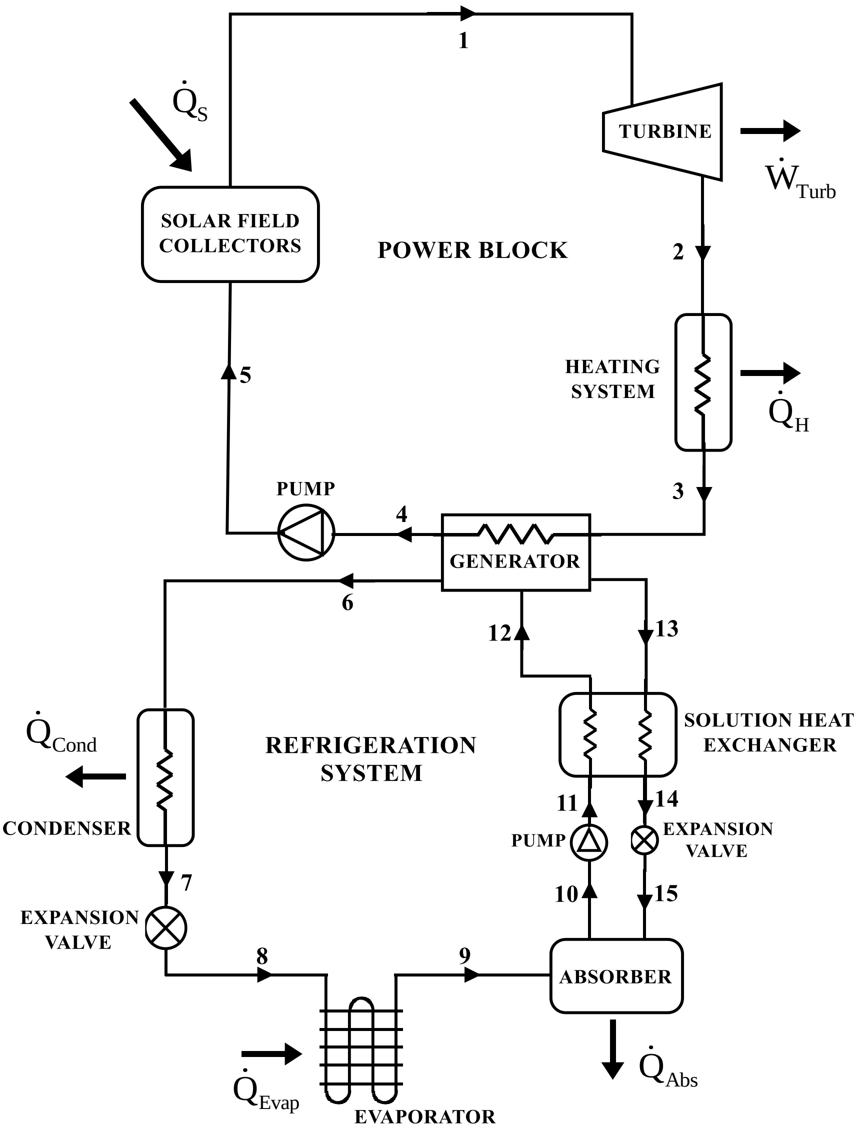


Figure 1. Trigeneration plant.

- *Turbo generator set*

The model adopted for the turbine was based on energy balance in steady state and the isentropic efficiency of the same, as shown in Eq. (1).

$$\dot{W}_{turb} = \dot{m}_1 \cdot \left(h_1 - h_2\right) \cdot \eta_{turb} \tag{1}$$

Where $\dot{W}_{turb}$ is the turbine power output, $\dot{m}_1$ is the mass flow, h_1 and h_2 are the work fluid inlet and outlet enthalpies of the turbine work fluid respectively and η_{turb} is the isentropic efficiency of the turbine.

- *Heating system*

The heating system comprises a heat exchanger that by cooling of the working fluid, generates heat to be consumed in a thermal process. The energy balance of the heat exchanger is shown in Eq. (2).

$$\dot{Q}_H = \dot{m}_2 \cdot h_2 - \dot{m}_3 \cdot h_3 \tag{2}$$

With $\dot{m}_2 = \dot{m}_3$ been the mass flow passing through the heat exchanger; h_2 and h_3 the inlet and outlet enthalpy; $\dot{Q}_H$ the heating heat rate of the process.

Table 1. Input variables and parameters of the simulation.

DEFINITION	VALUE
Turbine Efficiency	80%
Electric generator efficiency	95%
Pumps efficiency	80%
Solar collector's efficiency	60%
Electric power generated	500 kW
Water temperature at the outlet of the solar collectors	600 K
Pressure drop in solar collectors	20%
Inlet pressure in the solar collectors	0.2 MPa
Irradiance	850 W/m²
Strong ammonia solution pressure - water in the generator inlet of the absorption cycle	1.35 MPa
Strong ammonia solution temperature - water in the generator inlet of the absorption cycle	353 K
Ammonia steam temperature in the condenser inlet of the absorption cycle entry	363 K
Temperature of the liquid ammonia at the outlet of the condenser	308 K
Pressure of humid ammonia vapor at the evaporator inlet of the absorption cycle	0.55 MPa
Outlet temperature of the saturated steam from the ammonia absorption cycle evaporator	283 K
Inlet pressure in the turbine	2 Mpa
Inlet temperature in the turbine for N-octane, R123 and Novec649	570 K
Inlet temperature in the turbine for Water	720 K
Outlet pressure in the turbine for N-octane	0.085 Mpa
Outlet pressure in the turbine for Novec649	0.2 Mpa
Outlet pressure in the turbine for Water	0.32 Mpa
Outlet pressure in the turbine for R123	0.7 Mpa

- *Refrigeration system*

The absorption refrigeration system using ammonia as a working fluid takes advantage of the heat rejected by the power cycle. Upon exiting the heat exchanger of the heating system, the working fluid still remains in the condition of superheated steam. It passes through the generator of the absorption and then through the power block pump, which increases it pressure. The mass and energy balances of ammonia in each equipment that make up the refrigeration system are shown in Tab. 2.

Table 2. Equations used in the cooling system.

Energy balance in Condenser	$\dot{Q}_{cond} = \dot{m}_7 \cdot h_7 - \dot{m}_6 \cdot h_6$	(3)
Energy balance in the evaporator	$\dot{Q}_{evap} = \dot{m}_9 \cdot h_9 - \dot{m}_8 \cdot h_8$	(4)
Energy balance in Absorber	$\dot{Q}_{abs} = \dot{m}_{15} \cdot h_{15} + \dot{m}_9 \cdot h_9 - \dot{m}_{10} \cdot h_{10}$	(5)
Ammonia mass balance in Absorber	$\dot{m}_{15} \cdot x_{15} - \dot{m}_{10} \cdot x_{10} + \dot{m}_9 \cdot x_9 = 0$	(6)
Energy balance in the cooling system of the exchanger	$\dot{m}_{12} \cdot h_{12} - \dot{m}_{11} \cdot h_{11} = \dot{m}_{13} \cdot h_{13} - \dot{m}_{14} \cdot h_{14}$	(7)
Energy balance in generator	$\dot{Q}_{ger} = -\dot{m}_{12} \cdot h_{12} + \dot{m}_6 \cdot h_6 + \dot{m}_{13} \cdot h_{13}$	(8)
Mass balance of ammonia in the generator	$\dot{m}_{12} \cdot x_{12} - \dot{m}_{13} \cdot x_{13} - \dot{m}_6 \cdot x_6 = 0$	(9)
Energy balance in the expansion devices	$h_7 = h_8$ e $h_{14} = h_{15}$	(10)

In Table 2: $\dot{m}_i$, x_i and h_i represents the mass flow, ammonia mass fraction and enthalpy of each point respectively. $\dot{Q}_{cond}$, $\dot{Q}_{evap}$, $\dot{Q}_{abs}$ and $\dot{Q}_{ger}$ are the Condenser, Evaporator, Absorber and Generator exchange heat rates respectively. The heat exchange of the generator can also be expressed by Eq. (11).

$$\dot{Q}_{ger} = \dot{m}_4 \cdot \dot{h}_4 - \dot{m}_3 \cdot \dot{h}_3 \qquad (11)$$

- Power Block pump

The energy balance in the power block pump is shown in and Eq. (4):

$$\dot{W}_P \cdot \eta_P = \dot{m}_4 \cdot \left(h_5 - h_4\right) \qquad (12)$$

Where $\dot{W}_P$ is the pump power input; η_P the isentropic pump efficiency; $\dot{m}_4$ the fluid mass flow; h_4 and h_5 the inlet and outlet enthalpies respectively. The energy balance for the cooling system pump are similar to Eq. (12).

- Solar collectors

The energy balance in this equipment are presented by the Eq. (13) and (14).

$$\dot{Q}_S = \dot{m}_1 \cdot \dot{h}_1 - \dot{m}_5 \cdot \dot{h}_5 \qquad (13)$$

$$\dot{Q}_S = I \cdot A \cdot \eta_{coll} \qquad (14)$$

Where $\dot{Q}_S$ is the solar radiation heat rate; I the irradiance in the solar collectors; A the aperture area of the solar collectors; $\dot{m}_1 = \dot{m}_5$ the working fluid mass flow through the solar field; h_5 and h_1 the solar field inlet and outlet enthalpies respectively and η_{coll} the solar collector's efficiency.

3.2.2 Exergy Analysis

The Exergy analysis based on the first and second laws of thermodynamics overcomes some limitations that energy analysis shows and is an important tool to evaluate thermal systems (Bejan, 1996). This study shows the equipments with the highest exergy destruction, and, hence, higher irreversibility, thereby enabling better understanding of the processes and technologies involved. The exergy is defined as the maximum work that can be obtained from a system at a given thermodynamic state. The exergy rate destroyed in a volume control for a steady state is defined by Eq. (15).

$$\psi_d = \sum_j \left(1 - \frac{T_0}{T_j}\right) \cdot \dot{Q}_j - \dot{W} + \sum_i \dot{m}_i \cdot \left(h_i - T_0 \cdot S_i\right) - \sum_o \dot{m}_o \cdot \left(h_o - T_0 \cdot S_o\right) \qquad (15)$$

Where $T_j, \dot{Q}_j$ and W_j are the temperature, heat rate and power input respectively. With $\dot{m}_i$, h_i and s_i been the inlet mass flow, enthalpy and entropy. $\dot{m}_o$, h_o and s_o been the outlet mass flow, enthalpy and entropy. And T_0 been the environment temperature.

The exergy efficiency of trigeneration is an important factor to be considered in the cycle, defined as the ratio of the recovered exergy and exergy supplied to the system. For the trigeneration system proposed total exergy efficiency was modeled as Eq. (16).

$$\eta_{II} = 1 - \frac{\psi_{d,tot}}{\psi_{coll}} \qquad (16)$$

Where $\psi_{d,tot}$ is the system total exergy destruction and ψ_{coll} is the total exergy available in the system by the solar collectors.

For solar collectors, the input exergy due to radiation is defined by Eq. (17) (Patela, 2005).

$$\psi_{coll} = A \cdot I \cdot \left(1 + \left(\tfrac{1}{3} \right) \cdot \left(\tfrac{T_0}{T_S} \right)^4 - \left(\tfrac{4}{3} \right) \cdot \left(\tfrac{T_0}{T_S} \right) \right) \quad (17)$$

Where A is the solar collector's aperture area; I the irradiance in the solar collectors and T_0 e T_S the environment and sun temperatures respectively.

4. RESULTS AND ANALYSIS

In this work, the exergetic efficiency of trigeneration, the destruction of exergy in the collector field, turbine, generator and the heater system are evaluated by changing the fluid type of the power block system. This section presents the results obtained and the relevant discussions of the data found.

4.1 Results and discussion of the energy and exergy analysis of the trigeneration system

4.1.1 Fluid selection

The trigeneration system exergy was analyzed using EES with four kinds of fluids. The second law efficiency and solar field area are shown in tab. 3.

Table 3. Exergy efficiency of the trigeneration system for different work fluids.

Fluid	Area [m ²]	η_{II}[%]
N − octane	8057	15.92
Novec649	12517	11.19
R123	14911	10.22
Water	7333	17.82

With the chosen set up of water in the Fresnel trigeneration system, it is possible to obtain a higher exergy efficiency and a relatively low solar field area, however, the turbine inlet temperature is too high, which promotes heat loss through pipes and high material costs in the project. Besides other working fluids promote a smaller exergetic efficiency they are less environment friendly than water.

In Table 4 the variables and thermodynamic properties obtained by EES, in each point in trigeneration system, when water is used as working fluid are shown.

Table 4. Thermodynamic properties of the system proposed points using water as the working fluid.

Points	Flow rate [Kg/s]	T [K]	P [MPa]	h [kJ/Kg]
1	1.346	720.0	2.00	3351
2	1.346	529.5	0.32	2979
3	1.346	408.9	0.32	1791
4	1.346	408.9	0.32	573
5	1.346	409.1	2.00	573
6	0.962	363.2	1.35	1478
7	0.962	308.2	1.35	146
8	0.962	280.8	0.55	146
9	0.962	283.0	0.55	965
10	9.389	313.2	0.55	-34
11	9.389	319.2	1.35	-33
12	9.389	353.2	1.35	130
13	8.428	363.2	1.35	171
14	8.428	323.0	1.35	-11
15	8.428	323.0	0.55	-11

Compared to water, N-octane and Novec649 provides a low pressure after the turbine outlet, for the same output work. But, the water can work at high enthalpies at the turbine inlet. So the fluid selection depends on each case of the system application. For the selected configuration of the system of this paper, water was the best option. An economic study is also relevant for the installation and Operation and maintenance (O&M) of the system.

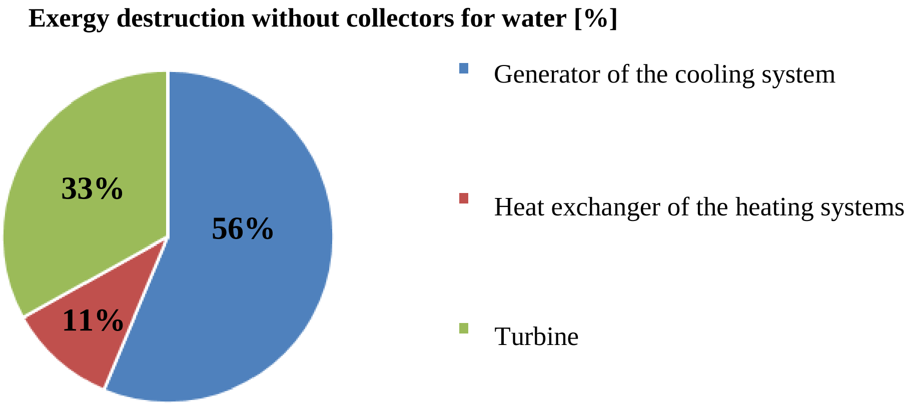
4.1.2 Exergy destruction analysis

The most exergy destruction occurred by far in the collectors of the solar field as shown in Tab. 5. The fluid that destroyed the less exergy in the collectors and in total, with its system configuration was the water.

Table 5. Exergy destruction in main components of the trigeneration system for different work fluids.

Fluid	$\Psi_{d,coll}$ [kW]	$\Psi_{d,t}$ [kW]	$\Psi_{d,gen}$ [kW]	$\Psi_{d,h}$ [kW]	Total [kW]
N-octane	4754	92.13	125.10	140.40	5111.63
Novec649	7783	87.50	146.90	70.39	8087.79
R123	8463	85.74	254.80	93.11	8896.65
Water	4319	94.07	160.10	30.10	4603.27

Analyzing the others equipment, it was possible to notice that the generator of the refrigeration system represented the higher exergy destruction, followed by the turbine and the heat exchanger of the heating system, as shown in Grap. 1 for the system working with water as operation fluid.



Graphic 1. Exergy destruction analyze

5. CONCLUSION

This paper evaluated a combined trigeneration system using solar energy as an energy source, and a Rankine Cycle to generate electricity. The exergy destruction in the system equipment and total exergy efficiency were evaluated. The main findings were as follows: (a) the further destruction of exergy occur by far in the solar collectors more than 90% of total exergy destroyed. Thus, a detailed study on receipt of solar radiation, which enables a lower exergy destruction would be quite relevant; (b) water shown to be the best choice for the proposed system. With the Fresnel technology, the needed conditions can be achieved using water as working fluid; (c) withdrawing the collectors, the exergy destruction in the generator of the refrigeration system was 56% of the exergy destruction of the main equipment of the system for the case of using water as the work fluid.

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