THERMODYNOAMIC ANALYSIS OF THREE SOLAR THERMAL POWER PLANTS

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ABSTRACT

A very important component to achieve sustainable development in the energy sector is the improvement of energy efficiency of widely applied thermodynamic processes. Evaluation and optimization methods of energy processes play a crucial role in fulfilling this goal. A suitable method for the evaluation and optimization of energy conversion systems has been proven to be the exergetic analysis.

In this work, three parabolic trough solar thermal power plants are simulated using commercial software, and they are further analyzed and compared using exergetic analysis. The goal is to detect thermodynamic inefficiencies of the three different configurations and propose measures to minimize them.

The first simulated solar thermal plant uses a thermal fluid to produce the steam required in a steam generator, the second plant produces the steam directly in the solar field, while the third power plant is used to find trade-offs between the first two alternatives by generating part of the necessary steam using a thermal fluid and part of it in the solar field. The analysis involves the evaluation of the individual components of the power plants, as well as the performance evaluation of the overall structures.

When examining the first two simulated plants, we find similar main sources of exergy destruction: the solar field (parabolic trough solar collectors), followed by the steam generator. This shows the importance of an optimal design of these particular components, which could reduce inefficiencies present in the system. Performing a sensitivity analysis using the configuration of the third available power plant we find the best possible combination that minimizes the thermodynamic inefficiencies of the first two alternatives for the generation of steam. The differences in the exergy destruction and exergetic efficiencies of individual components of the three plants are analyzed based on comparable operational conditions.

The analysis shows the convenience of using a hybrid configuration where steam is directly generated in the solar field, white it is reheated using a heat transfer fluid.

Keywords: Exergy analysis, Solar plant, Solar trough collectors.

1. Introduction

An exergy analysis is a suitable method for the evaluation of the efficiency of a wide range of energy systems and processes [1, 2]. A conventional exergetic analysis reveals irreversibilities within plant components and it represents the first step to evaluate the cost of these irreversibilities in a subsequent exergoeconomic analisis.

Solar thermoelectric technology is still in its start-up phase despite the existence of experimental plants since the 1980s. Therefore, the application of an exergy analysis to the design of this type of plants can play an important role in the improvement of the efficiency and the reduction of costs. Exergy analysis has been applied to a variety of solar technologies and configurations, including parabolic trough collectors [3, 4]. In these studies the use of different types of fluids (such as oil, water/stem or molten salt) and the influence of operational and environmental parameters are discussed. The overall process has been examined with exergy analysis in order to discuss the influence of selective operative conditions: such as pressure, location and others [6]. A limited number of publications deal with the analysis and comparison of different plant configurations. Fahad A. Al-Sulayman [5] carried out a detailed exergy analysis of selected thermal power systems driven by parabolic trough solar collectors.

Although comparative analyses among different plant configurations exist and can be very useful to improve the efficiency of a plant and its individual components, they do not exist yet by means of an exergy analysis. For example, A. Giostri et al. [7] compare five different parabolic trough plants in terms of an energy analysis and they propose a hybrid configuration, which combines advantages of direct steam evaporation and the use of a heat-transfer fluid as the best option to increase the thermodynamic efficiency. The aim of this work is to evaluate different configuration possibilities of the design of a parabolic trough solar collector thermal power plant by means of an exergy analysis.

2. Plants description

2.1. Heat-Transfer fluid (HTF)

The first plant is a solar plant using parabolic through collectors and a heat-transfer fluid to carry the heat adsorbed in the collectors to three superheaters and a reheater where steam is produced. A diagram of the plant is shown in Figure 1.

2.2. Direct steam generation (DSG)

In the second plant, steam is directly produced in the solar field, that is to say, inside the collector tubes. Hence the solar field has been split into two sections: one primary zone where steam is produced, and a secondary zone where steam exiting the turbines is reheated. The detailed structure of the plant can be seen in Figure 2.

2.3. Hybrid configuration (HYB)

Hybrid configurations are usually proposed to combine advantages of direct steam generation and indirect cycles using a HTF [7]. In the third plant used in this paper, the solar field is divided into two sections: the first section performs direct steam evaporation, as in the DSG configuration, while in the second section, a conventional HTF is heated and used for steam reheating. The structure of this plant is shown in Figure 3.

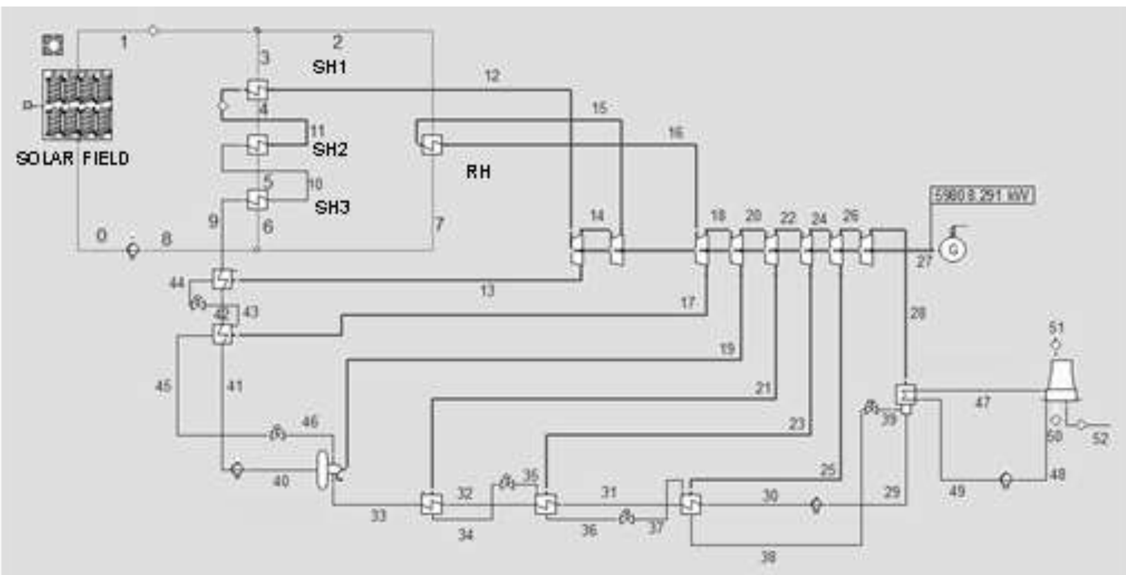

Figure 1: Detailed structure of the solar plant with the heat-transfer fluid.

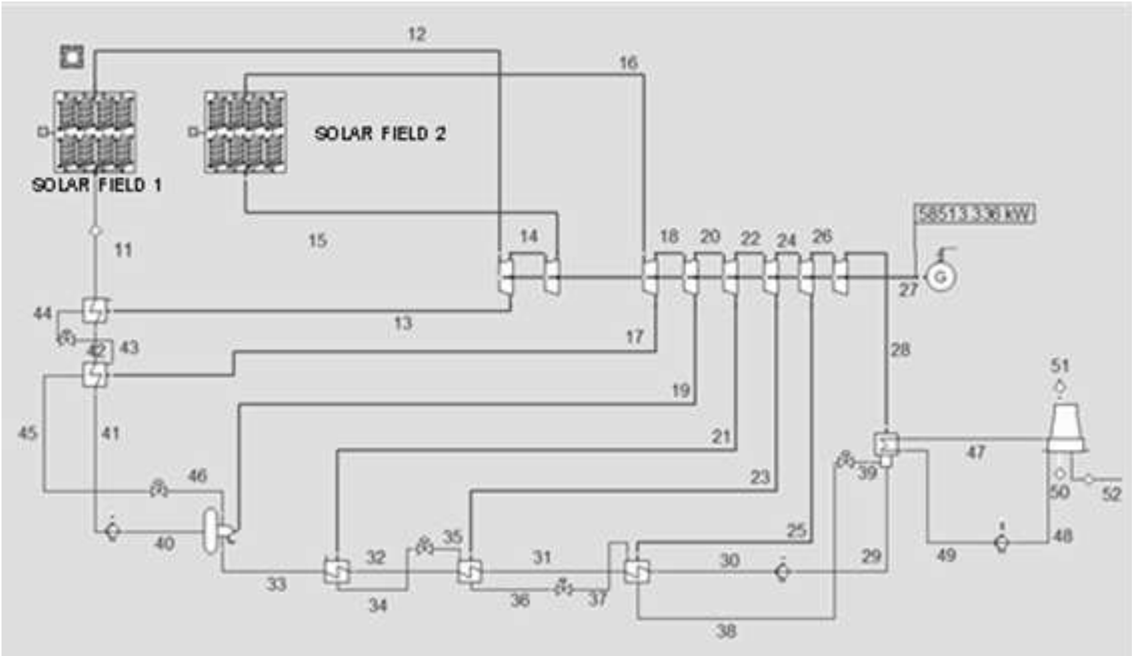

Figure 2: Detailed structure of the solar plant with direct steam generation.

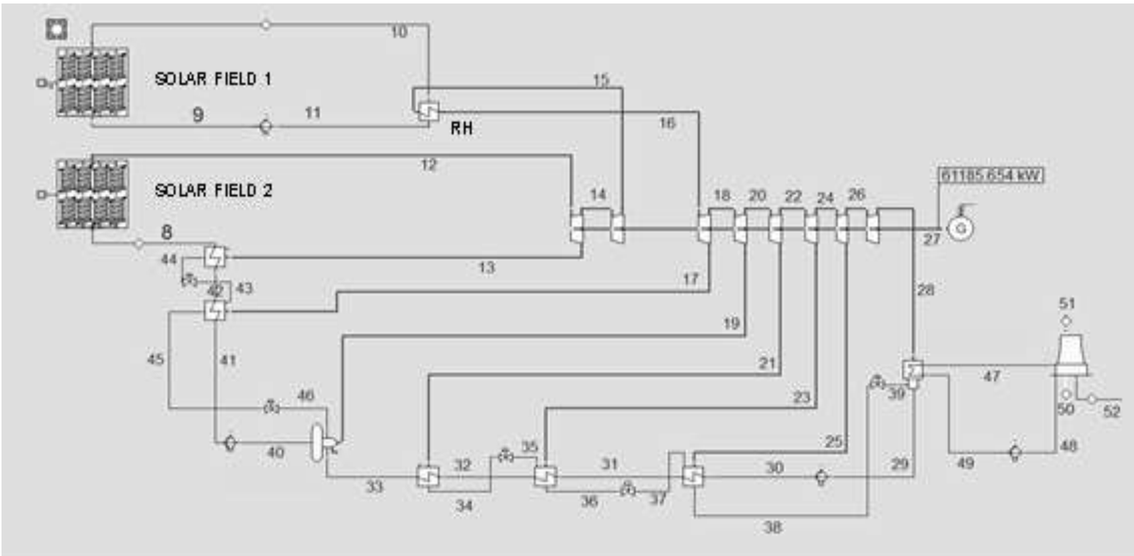

Figure 3: Detailed structure of the hybrid solar plant.

3. Methodology

The evaluation of the three plants has been performed at the component level using an exergy analysis. The initial data needed for the analysis are: (i) at the stream-level mass flow, temperature, enthalpy and entropy that were obtained by simulating the plant in the software EbsilonProfessional; (ii) the amount of solar radiation: an average solar radiation of 1000 W/m^2 has been assumed and (iii) the ambient conditions: 298 K and 1 atm.

The rate of exergy of the product of component k, $E_{P,K}$, is the exergy of the desired output resulting from the operation of the component, while the rate of exergy of the fuel of the same component, $E_{F,K}$, is the expense in exergetic resources for the generation of the desired output. The rate of exergy destruction within component k, $E_{D,K}$, is calculated as the difference between its rate of fuel and product exergy ($E_{D,K} = E_{F,K} – E_{P,K}$). General guidelines for defining exergetic efficiencies have been proposed by Lazzaretto and Tsatsaronis (2006) and have also been used here.

Other important variables of the exergetic analysis are the exergy destruction ratio, y_D, and the exergy loss ratio, y_L. The latter is only defined for the overall system. The exergy destruction ratio can be used to compare dissimilar components of the same system, while the total exergy destruction and exergy loss ratios can be used to compare different thermodynamic systems. Using the mentioned data and methodology [1, 8, 9] an exergy analysis has been performed.

4. Results

The differences in the exergy destruction and exergetic efficiencies of individual components of the three plants are analyzed in detail based on comparable operational conditions. The results obtained are shown in Tables 1, 2 and 3.When examining the first two simulated plants, we find similar main sources of exergy destruction: the solar field (parabolic trough solar collectors), followed by the steam generator (superheaters, *SH* and reheaters, *RH*). In the first one, a 69.9 % of the exergy is destroyed in the solar field and a 4.4 % in the steam generator. If a direct steam generation configuration is used (second plant, Table 2) exergy losses in the steam generator are avoided, but the exergy destruction in the solar field increases to 74.6 %.

Table 1: Results at the component level for the plant using thermal fluid (only selected components).

Component, k	$E_{F,k}$ (MW)	$E_{P,k}$ (MW)	$E_{D,k}$ (MW)	ε_k (%)	$y_{D,k}$ (%)
Solar field	273.6	82.2	191.3	30.1	69.,94
SH1	7.4	6.6	0.8	88.7	0.31
SH2	46.5	40.3	6.2	86.6	2.28
SH3	14.6	12.5	2.1	85.8	0.76
RH	14.2	11.3	2.9	79.4	1.07
TOTAL	**273.6**	**59.8**	**219.0**	**21.9**	**80.07**

Table 2: Results at the component level for the plant with direct steam generation (only selected components).

Component, k	$E_{F,k}$ (MW)	$E_{P,k}$ (MW)	$E_{D,k}$ (MW)	ε_k (%)	$y_{D,k}$ (%)
Solar field 1	228.5	61.3	167.2	26.8	61.13
Solar field 2	45.1	8.1	37.0	17.9	13.52
TOTAL	**273.6**	**58.5**	**217.6**	**21.4**	**79.53**

Table 3: Results at the component level for the hybrid plant (only selected components).

Component, k	$E_{F,k}$ (MW)	$E_{P,k}$ (MW)	$E_{D,k}$ (MW)	ε_k (%)	$y_{D,k}$ (%)
Solar field 1	225.3	65.6	159.7	29.1	58.37
Solar field 2	48.3	16.0	32.3	33.1	11.80
RH	16.0	13.1	2.9	82.2	1.04
TOTAL	**273.6**	**61.2**	**210.5**	**22.4**	**76.95**

Performing a sensitivity analysis using the configuration of the third available power plant we find the best possible combination that minimizes the thermodynamic inefficiencies of the first two alternatives for the generation of steam. In fact, while in the two first plants approximately 80 % of the exergy is destroyed, this value decreases to 77 % in the plant with the hybrid configuration.

5. Conclusions

The efficiency of solar through collector plants can be analysed be means of an exergy analysis. In this work three alternative solar plants have been analyzed using an exergy analysis. This analysis showed the convenience of using hybrid configurations where steam is directly generated in the solar field, while it is reheated using a heat transfer fluid.

REFERENCES

1. Bejan A, Tsatsaronis G, Moran M. Thermal design and optimization. New York: Wiley; 1996.
2. Tsatsaronis G. Definitions and nomenclature in exergy analysis and exergoeconomics. Energy 32 (2007) 249–253.
3. Montes M, Abánades A, Nades A, Martinez-Val J, Thermofluidynamic model and comparative analysis of parabolic trough collectors using oil, water/steam, or molten salt as heat transfer fluids, J. Sol. Energy Eng. 132 (2) (2010).
4. Vasquez-Padilla R, Montalvo A, Demirkaya G, Martinez A, Gonzalez A. Exergy analysis of parabolic trough solar receiver. Applied Thermal Engineering 67 (2014) 579-586.
5. Siva Reddy V, Kaushik S.C, Tyagi S.K. Exergetic analysis and performance evaluation of parabolic trough concentrating solar thermal power plant (PTCSTPP). Energy 39 (2012) 258-273.
6. Al-Sulaiman F.A. Exergy analysis of parabolic trough solar collectors integrated with combined steam and organic Rankine cycles. Energy Conversion and Management 77 (2014) 441–449.
7. Giostri A, Binotti M, Astolfi M, Silva P, Macchi E, Manzolini G. Comparison of different solar plants based on parabolic trough technology. Solar Energy 86 (2012) 1208–1221.
8. Lazzaretto A, Tsatsaronis G. Speco: a systematic and general methodology for calculating efficiencies and costs in termal systems. Energy 2006;31:1257-89.
9. Tsatsaronis G, Cziesla F. Thermoeconomics. In: Enciclopedia of physical science and technology. Academic Press; 2002. p. 659-80.