# Maximum Thermodynamic Efficiency of a Conceptual Direct Steam Generation Solar Power Plant

## Preprint

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# MAXIMUM THERMODYNAMIC EFFICIENCY OF A CONCEPTUAL DIRECT STEAM GENERATION SOLAR POWER PLANT

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## ABSTRACT

*In the present work, the maximum theoretical limit of a direct steam generation solar plant is discussed under the theory of endoreversible and classical thermodynamics, comparing it with the estimated efficiency in operating conditions. The solar plant uses optical optimized Fresnel reflectors for direct steam generation to feed two Rankine cycle configurations, with two and three steam extractions respectively. The steam extractions pressure was determined considering the minimum entropy generation in the cycle to maximize the thermal efficiency. As a result of optimizing the generation of entropy, the analyzed plant has a thermal efficiency very close to that of an endoreversible engine, so it can be established that the Rankine cycles discussed will be operating at practically the maximum power output under the physical limits of the plant itself system.*

Keywords: Endoreversible, solar plant, thermal efficiency, direct steam generation

## NOMENCLATURE

| | |
|---|---|
| $\eta$ | efficiency |
| C-A | Curzon-Ahlborn |
| ERT | endoreversible thermodynamics |
| FTT | finite time thermodynamics |
| $Q$ | heat |
| $T$ | temperature |
| $W$ | work |

## 1. INTRODUCTION

The thermal efficiency of any power plant will always have as its upper limit the thermal efficiency of an internally and externally reversible motor (Carnot). However, in the middle of the 20th century, power systems have been modeled that considering the irreversible heat transfer process between the high and low-temperature reservoirs, and internally reversible engines [1], [2]. This model is known as endoreversible thermodynamics (ERT) or finite time (FTT) [3], [4]. In classical thermodynamics, temperature reservoirs transfer thermal energy reversibly, that is, they have two conditions: a finite heat transfer time or an infinite conductance. However, heat transfer postulates that the energy transfer via heat occurs in a time delimited by equilibrium conditions and that there are no real devices that present infinite conductance [5], [6]. It has been shown that in the limiting case that one of these conditions is met, the useful work of the cycle turns out to be zero [7], which contradicts the purpose of generating energy through power cycles. The concepts addressed by the ERT do not provide any new definitions; however, it allows a more objective comparison of the thermal efficiency of real power plants with the maximum theoretical that can be achieved [8]. In Table 1, the efficiency of real plants is compared with the Carnot efficiency [9], modeled by Eq. (1), and the Curzon-Ahlborn (C-A) efficiency [2], modeled by Eq. (2). It is seen that the C-A model exhibits a more realistic efficiency for the observed in real power plants.

Table 1. Thermal efficiency observed in real thermal power plants [3], [10].

| | $T_H$ | $T_L$ | Carnot | C-A | Observed |
|---|---|---|---|---|---|
| | [°C] | | | | |
| West Thurrock (coal fired steam power plant - England) | 565 | 25 | 0,64 | 0,40 | 0,36 |
| Landerello (geotermal power plant - Italy) | 250 | 80 | 0,32 | 0,18 | 0,16 |
| Punta prieta (flueloil steam power plant - Mexico) | 513 | 28 | 0,62 | 0,38 | 0,35 |
| Tula (combined cicle - Mexico) | 542 | 23 | 0,64 | 0,40 | 0,38 |

$$\eta_C = 1 - \frac{T_L}{T_H} \tag{1}$$

$$\eta_{C-A} = 1 - \sqrt{\frac{T_L}{T_H}} \tag{2}$$

By relating the power that a cycle can deliver, depending on the thermal efficiency, it is possible to obtain the graph shown in Fig. 1. It is observed that the power of the cycle increases with the thermal efficiency, reaching a maximum when the performance corresponds to that of C-A and then abruptly decreases; and that it tends to zero as the thermal performance approaches that of Carnot.

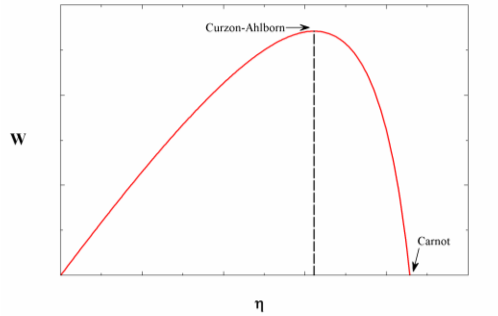


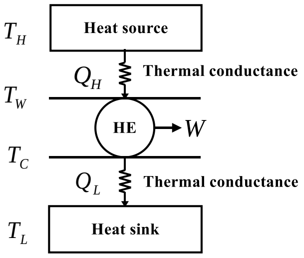
**FIGURE 1:** POWER OF A THERMODYNAMIC CYCLE AS A FUNCTION OF THE TEMPERATURES OF THE THERMAL RESERVOIRS.

## 2. ENDOREVERSIBLE THERMODYNAMICS MODEL

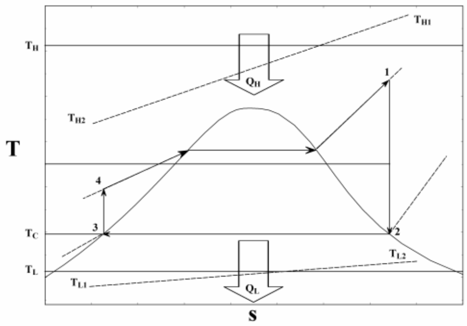
Today there is already a vast theory that allows different thermodynamic cycles (power and cooling) to be analyzed under the analysis of finite times or through finite conductances [11]; that has been applied with relative success in solar thermal systems [7], [12]–[15], and also to different conventional power plants in Mexico [10], where it has been proven that ERT models the behavior of these systems in a more suitable manner. Since there is a temperature difference between the heat source and the working fluid in the heating and cooling processes, there is an irreversible heat transfer in the system, so a simplified model of the cycle can be seen in Fig. 2 (a). In the present work, a Rankine cycle characterized by a heat source with finite conductance is analyzed, as seen in Fig. 2 (b). The thermal efficiency of a Rankine cycle under ERT conditions is modeled in the same way as in Eq. (2), where the temperature values correspond to the limits of each heat sink, that is, the maximum theoretical yield under the T-ER scheme will be $\eta_m = 1 - \sqrt{\frac{T_{L1}}{T_{H1}}}$.

## 3. CASE OF STUDY

The ERT analysis is carried out in a 10 $MW$ conceptual solar thermal plant that uses direct steam generation Fresnel reflectors that will feed a Rankine cycle with two and three steam extractions, as outlined in Fig. 3; located in Agua Prieta, Mexico. Once the configuration of the power block has been defined, each state is characterized where a sensitivity analysis has been carried out to establish the optimal extraction pressures [16] to minimize the entropy generation of the cycles [3], [17], see Fig. 4, and finally stablish each thermodynamic state Fig 5.

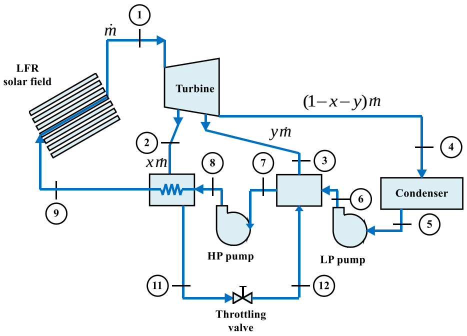


(a) Simplified engine model

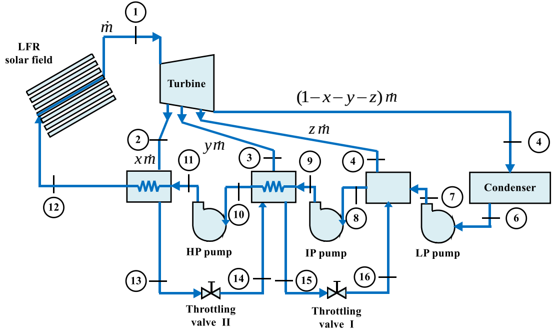


(b) T-s diagram of a Rankine cycle

**FIGURE 2:** ERT engine model



(a) 2 steam extractions



(b) 3 steam extractions

**FIGURE 3:** Schematic diagram of the power cycle configurations.

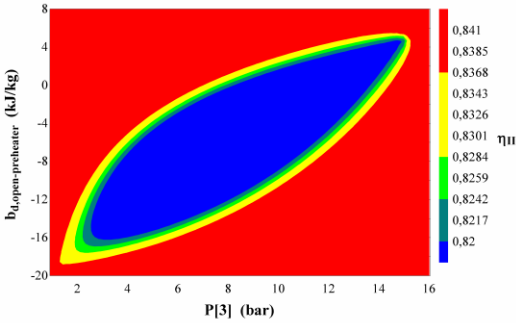
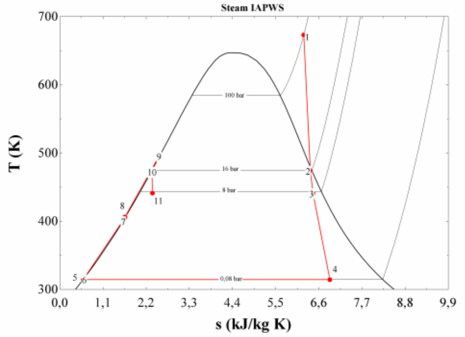
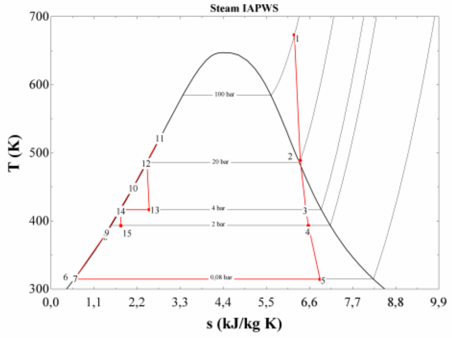


**FIGURE 4:** ENTROPY GENERATION OPTIMIZATION.



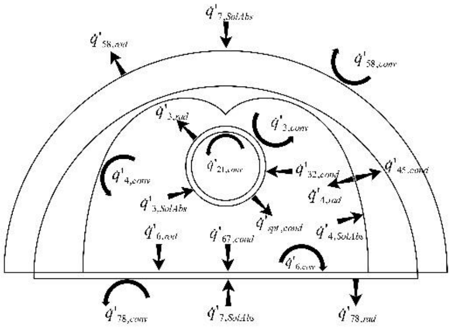
(a) 2 steam extractions



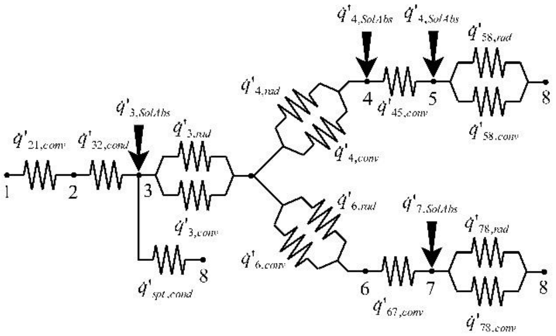
(b) 3 steam extractions

**FIGURE 5:** Schematic diagram of the power cycle configurations.

With the thermodynamic characterization, it is possible to establish the size of the field of Fresnel reflectors that will allow us to deliver the necessary thermal energy to achieve the necessary conditions at the turbine inlet and to be able to feed the cycle. In the case of the 2 steam extractions cycle, it is required to heat $12{,}81\ kg\ /\ s$ of water from $496{,}1\ K$ to $673{,}2\ K$. For the 3 steam extractions cycle, it is required to heat $13{,}26\ kg\ /\ s$ of water from $485{,}5\ K$ to $673{,}2\ K$ [16]. The ERT model requires knowing the temperature of the high-temperature source, that is, the surface temperature of the absorber tube of the Fresnel reflector. In the present study, a Fresnel reflector field is considered that has been optimized to increase the interception factor and achieve a smaller loop [18], taking as a reference the description of the FRESDEMO loop [19]. The optimized field was thermodynamically characterized by a detailed one-dimensional analysis of heat transfer in the receiver [20], see Fig. 6.



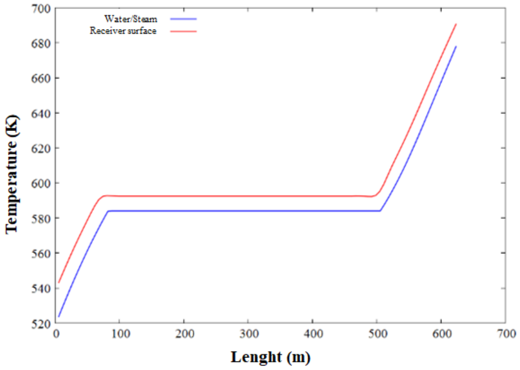
(a) Fresnel receiver cross-section



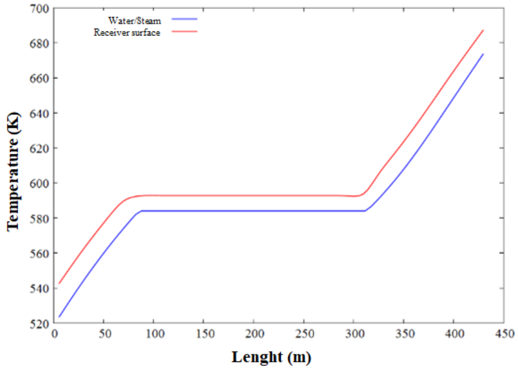
(b) Receiver thermal resistance model

**FIGURE 6:** Heat transfer model [20].

The graphs that are shown in Fig. 7 correspond to the temperature of the water and the outer surface of the tube along the loops corresponding to the Rankine cycles with two and three vapor extractions for a solar field with three loops of Fresnel reflectors. As can be seen, there is a difference in temperature between the working fluid and the surface of the tube. Thus, it is possible to make an analogy between the high-temperature source of Fig. 2 and the surface temperature of the absorber tube.



(a) Fresnel receiver cross-section



(b) Receiver thermal resistance model

**FIGURE 6:** Heat transfer model [20].

## 4. THERMAL EFFICIENCY COMPARISON

With the thermodynamic characterization, in conjunction with Eqs. (1) and (2), it is possible to plot the graph shown in Fig. 7; where the thermal efficiency of Carnot and C-A are plotted; and the efficiency presented by the thermodynamic characterization of each Rankine cycle analyzed is located respectively. The Rankine cycle with 2 steam extractions has a thermal efficiency of 0.31, and under these operating conditions, a Carnot engine would have a performance of 0,565, and a 0,38 for a C-A engine. The relative error with Carnot's performance is 0,451 versus 0,089 for C-A's performance. For the Rankine cycle with 3 steam extractions, the thermal efficiency is 0,315; a Carnot engine would have a performance of 0,563, and a 0,339 for a C-A engine. The relative error with Carnot's performance is 0,441 versus 0,072 for C-A's performance.

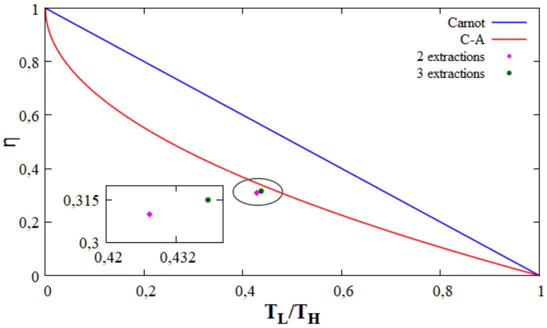


**FIGURE 7:** EFFICIENCY COMPARISON.

When comparing the relative error that exists between the calculated value with the thermodynamic characterization of the Rankine cycle against the efficiency of Carnot and that of C-A, it is evident that the C-A model more realistically models the maximum theoretical limit that we could reach with a cycle of power fed by a solar thermal system. This is explained by analyzing in detail the graphs shown in Fig. 6, where the difference in temperatures between the source and the water during heating can be seen, corresponding to process 1-2 of Figs. 5 (a) and (b). This temperature difference causes the irreversibility between the high-temperature reservoir and the working fluid, resulting in the efficiency of the Rankine cycles deviating too far from the maximum theoretical Carnot; however, since the extraction pressures have been optimized to minimize the generation of entropy, the internal irreversibilities in the cycle have been reduced, which makes the cycle performance too close to the maximum of C-A.

## 5. CONCLUSIONS

The ERT model acknowledges a more realistic analysis of the maximum theoretical limit that a real engine can approach, without the need to introduce new concepts to classical thermodynamics.

In the present study, the analysis of two Rankine cycles, fed by a field of Fresnel reflectors in steam generation, has been addressed.

Since the Rankine cycles analyzed present two and three vapor extractions, the thermodynamic states were determined under the premise of minimizing the generation of entropy, and thus being able to operate in the best possible conditions. Having optimized extraction pressures resulted in the estimated thermal efficiency of the Rankine cycles being too close to the limits proposed by Curzon and Ahlborn, so they would be operating almost at the limit of endoreversible thermodynamics.

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