# Simulation and parametric analysis of low pressure on the operation of a concentrated solar thermal installation

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**Abstract:**

The exploitation of solar energy has become a major concern, especially since our country holds a significant solar potential during the year. We can use concentrated solar energy to produce electricity or heat. This contribution consists, from simulations, in the parametric analysis of the operation of a solar concentration thermal installation, highlighting the direction of the variation of the thermal efficiency as a function of the low pressure for a machine working according to the ideal cycle of RANKINE. We were interested too:

- In the sense of the variation of the thermal efficiency as a function of the temperature of the superheat for an improved installation working according to the ideal cycle of HIRN
- At the influence of the overheating temperature for the HIRN cycle and low pressures for both cycles (RANKINE and HIRN), on the yield in order to propose a possible improvement.

Simulations for different modifications on the RANKINE and HIRN cycles show that for an increase in the superheat temperature, the reduction of the low-pressure lead to a better yield.

**Key words:** Influence, temperatures, pressures, solar thermal installation, solar tower, steam turbine, thermal efficiency of a steam turbine.

## I. Introduction

Solar (solar photovoltaic, solar thermal), hydropower, wind, biomass and geothermal energy are inexhaustible flows compared to "stock energies" from fossil fuel deposits in the process of becoming rare: oil, coal, natural gas [1] [2] [3] [4]and [5].

Therefore, the exploitation of renewable energies is recommended, we are interested in the use of solar energy by solar thermal power plants to meet the energy needs. The use of solar energy thermodynamically, in order to produce useful work, requires mastery and know-how in two related fields [6] [7] and [8]:

- capture and concentration,
- the thermodynamic conversion of the different aspects of energy.

## II. Principle of a solar power plant

The growing importance of solar thermal has led designers to significant progress in their studies (design features). This has been achieved, on the one hand by improving the heat absorption capacity by the solar collector by adding new functionalities to the plate absorber, [9] and on the other hand to the improvement of geometry [ 10] and the use of alternative materials [11] and [12].

### III. Principle of operation

Solar radiation can be focused on a linear or point receiver. The receiver absorbs the energy reflected by the mirror and transfers it to the thermodynamic fluid (Figure 1). This fluid at high temperature and pressure rotates a turbine to obtain mechanical energy, which will subsequently be used for multiple needs (industrial, domestic ...) **[13] [ 14] [15]** and **[16]**.

For the conversion of solar energy to easily exploitable mechanical energy, we go through two stages:

- Thermo-solar conversion;
- Thermodynamic conversion.

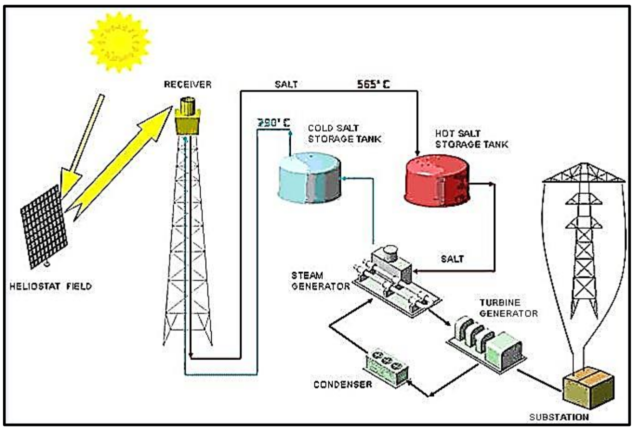


**Figure 1.** Schematic diagram of a concentrated solar power station

The daily solar cycle is known for its limited duration, hence the need to store the energy obtained for its use in the absence of the source of the latter. In order to increase the performance of solar thermal plants, an auxiliary boiler is often used to raise the temperature of the thermodynamic fluid.

### IV. Thermodynamic Conversion

#### IV.1. General Operation

The hot source (solar energy) heats (directly or indirectly) the heat transfer fluid which changes from the liquid state to the vapor state. The steam thus produced is admitted into a steam turbine where its expansion causes the wheels of the latter to rotate, coupled to an alternator, the mechanical energy is converted into electrical energy.

Steam condensed in a condenser at the outlet of the turbine (the condensation energy can be used for various needs), it is found in the liquid state. This condensate is returned to the heat transfer fluid system for a new vaporization cycle.

Cogeneration is the joint production of electricity and heat for an industrial process or district heating to improve overall efficiency [17] .

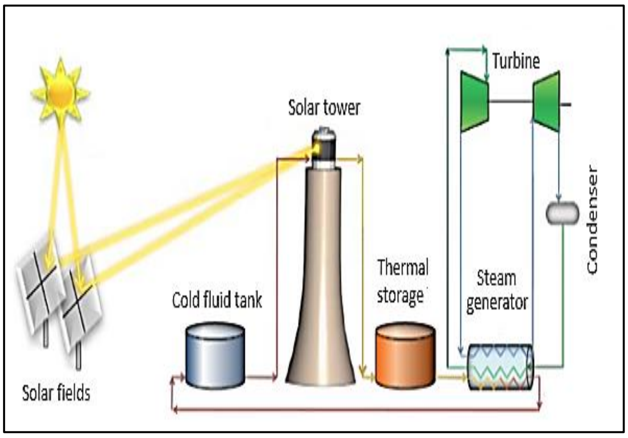


**Figure 2.** Principle of operation of a concentrated solar thermal power station **[17]**

### V. Study of the power plant

The plant is composed of two main parts:

- Thermo-solar;
- Steam installation.

#### V.1. Study of the thermo-solar part

Solar thermodynamic plants use a large amount of mirrors that converge the sun's rays to a heat transfer fluid heated at high temperature. To do this, reflective mirrors must follow the movement of the sun to capture and focus radiation throughout the daily solar cycle [18].

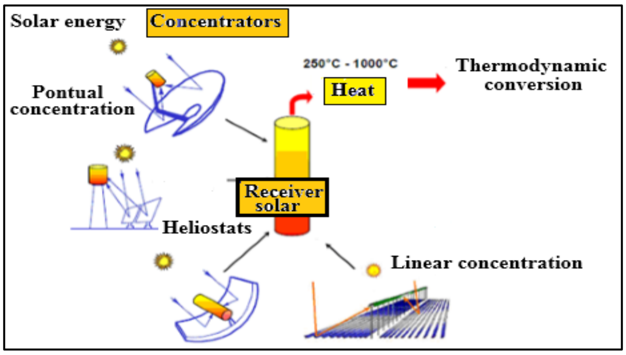


**Figure 3.** Global diagram of the solar-thermal conversion

In the solar-thermal part, the solar tower installation is chosen because of its high performance. It is composed of a heliostats field chasing the sun along the day and a receiver located in the top of a tower allowing the collection of all the solar rays in a concentrated way.

## VI. Transport and storage of heat

Thermal energy is produced in a remote site from where it must be converted into mechanical energy, the latter is continuously transformed into electrical energy. This, in order to transport and store thermal energy for the production to be constant all day to see every month of the year [19].

### VI.1. Heat transfer fluids

The thermal energy from the solar radiation collected is converted by a heat transfer fluid and a second thermodynamic. In some cases, the coolant is used directly as a thermodynamic fluid. The choice of the heat transfer fluid determines the maximum permissible temperature, guides the choice of the technology, the materials of the receiver and conditions the possibility of the convenience of storage [20].

### VI.2. Thermal storage

The operation of solar power generation systems is strongly constrained by the intermittences of the resource. To remedy this, some thermodynamic plants use thermal storage. This storage rarely reduces costs but considerably increases the value of electricity produced by improving the plant's output. Storage increases the operating time (capacity factor) of the plants compared to the available hours of sunshine, which typically ranges from 20% without storage to 30-50% with storage. It is a question of storing and restoring the thermal energy to the required power and at high temperature [21] [22].

The storage capacity is often expressed in hours of production at full load in the absence of solar radiation.

#### VI.2.1. Storage systems

We distinguish the following storage systems:

• ***Systems based on sensible heat***

Systems based on sensible heat in a liquid or gaseous medium are now fairly well controlled. For these technologies, the cost is moderate for a yield greater than 95%. However, this storage technique imposes a temperature variation of the material used between the charge and the discharge of the storage. This disturbs the pressure / temperature stability of the steam loop. Furthermore, the storage of sensible heat in a parabolic trough plant is problematic because the small difference in temperature between the inlet and the outlet of the field (about 100 ° C.) imposes storage volumes (and therefore costs). higher than those of tower plants with equivalent capacity.

• ***Systems based on latent heat***

Latent heat storage has two major interests:

- the storage and restitution phases: they are carried out at constant temperature imposed by the material used,
- the volume storage capacities: they are more important than in the case of sensible heat.

If the change in liquid-vapor phase has the highest capacities, the excessive volume of vapor produced favors the change of liquidsolid state. Never the less this approach is still experimental and still requires further work.

• ***Systems based on thermochemical cycle storage***

This type of storage implements that of energy in the heat of reaction of reversible chemical processes. Its feasibility has been demonstrated in the framework of the European project SOLZINC (2001-2005) concerning the solar carbon reduction of ZnO for the production of hydrogen.

### VI.2.2. Bottle of storage

A heat transfer fluid storage tank has a thermal storage capacity that varies according to its level of insulation and its physical volume. This type of storage is currently one of the most common ways of storing heat. But this solution is not without side effects [23].

After it has exhausted its energy in the use circuit, the heat transfer fluid returns to the thermal storage tank in its lower part; the fluid is relatively cold compared to that heated in the balloon because it has just lost its heat in the external system. In the balloon, the fluid warms up and goes up gradually where it is extracted to send it back into the circuit of use. However, during this cycle, the cold liquid entering the balloon creates a kind of cold jet that mixes directly with the liquid being heated; this chaotic phenomenon greatly reduces the quality of heat transfer and the entire system performance will be affected accordingly [23], [24] and [25].

Laminating techniques of the stored fluid improve the distribution of temperatures in the flask, which on the other hand decreases the heat losses due to the mixing phenomenon of the relatively cold fluid coming from the use circuit and the heated one. in the balloon [13].

## VII. Simulation optimization

Several optimization methods have been developed over time; some are inspired by the organization in the existing environment while others have been developed to meet the needs of specific scientific areas.

Today, the development of computer tools and simulation software makes it possible to model more and more advanced equipment and systems.

The geometric characteristics of the main balloon (volume and height) are two magnitudes that one seeks to optimize. In general, the procedure provides for variations of the magnitudes to be optimized in order to iteratively determine their values. A system to be optimized must have some freedom in these parameters.

For the purposes of this procedure, the volume of the balloon must be variable. Being cylindrical, its height and volume are directly related. Based on a sample from the thermal storage balloon market, we determined the relation between volume and height for volumes of less than 0.6 $m^3$ by a linear regression equation. For volumes greater than 0.6 $m^3$, the height is given by a relation (1) [26]:

$$H_{bln} = 1{,}737 . V_{bln} + 1{,}014 \quad \text{avec } V_{bln} < 0{,}6\, m^3 \tag{1}$$

$$H_{bln} = \max\left(\min\left(2{,}2\left(1{,}78 + 0{,}39 \ln\left(V_{bln}\right)\right), 1{,}25\right)\right): \; V_{bln} \geq 0{,}6\, m^3 \tag{2}$$

Or $H_{bln}$ is the height of the thermal storage balloon (m), $V_{bln}$ is the volume of the balloon $m^3$

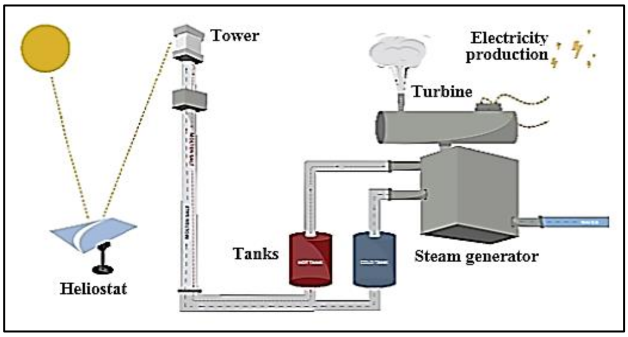


**Figure 4.** Simplifying diagram of the implementation **[18]**

## VIII. Thermodynamic study

The plant is intended for the exploitation of concentrated solar energy, with the aim of converting it into thermal energy, then mechanical following a thermodynamic cycle, so that it is finally available for a variety of operations.

Changes have been made on the RANKINE cycle of energy implantation to study the thermodynamic parameters, in order to improve the efficiency of the installation, our approach is to add an overheating (HIRN cycle) and see its influence on improving the performance of our machine.

- **RANKINE cycle**

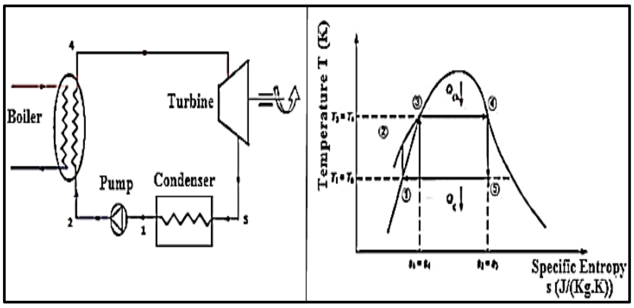


**Figure 5.** Schematic diagram of the RANKINE cycle

According to the first principle of thermodynamics, the energy balances of each element provide us with the following equations:

$$q_{Ch} = h_4 - h_2 \quad (3)$$

$$q_C = h_5 - h_1 \quad (4)$$

$$w_P = h_2 - h_1 \quad (5)$$

$$w_t = h_4 - h_5 \quad (6)$$

$$w_u = w_t - w_P = q_{Ch} - q_C \quad (7)$$

The yield is calculated as follows:

$$\eta = \frac{w_u}{q_{Ch}} = \frac{q_{Ch} - q_C}{q_{Ch}} \quad (8)$$

With:

$\boldsymbol{h_i}$: Mass enthalpies of the different points, [kJ / kg];

$\boldsymbol{q_{Ch}}$: Mass boiler heat, [kJ / kg];

$\boldsymbol{q_C}$: Condenser mass heat, [kJ / kg];

$\boldsymbol{w_P}$: Pump mass work, [kJ / kg].

By replacing equations (3) and (4) in the expression of the yield, we obtain:

$$\eta = \frac{h_4 - h_2 - (h_5 - h_1)}{h_4 - h_2} \quad (9)$$

$$\eta = \frac{h_4 - h_2 - (h_5 - h_1)}{h_4 - h_2 + h_1 - h_1} \quad (10)$$

$$\eta = \frac{h_4 - h_5 - (h_2 - h_1)}{h_4 - h_1 - (h_2 - h_1)} \quad (11)$$

With:

$$w_P = h_2 - h_1 = v.dP \quad (12)$$

$v$ : Mass volume.

This results in the final expression of the output:

$$\eta = \frac{h_4 - h_5 - v.dP}{h_4 - h_1 - v.dP} \quad (13)$$

- **HIRN cycle**

The HIRN cycle operates according to five transformations as shown in the diagrams of Figure 6:

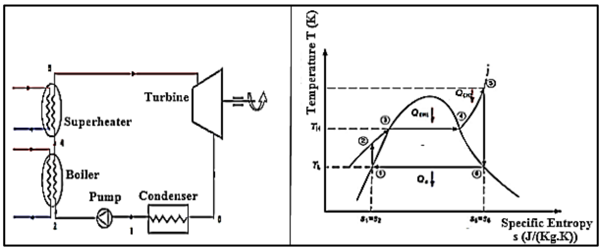


**Figure 6.** Schematic diagram of the HIRN cycle

According to the first principle of thermodynamics, the energy balance of each element gives us the following equations:

$$q_{Ch1} = h_4 - h_2 \quad (14)$$
$$q_{Ch2} = h_5 - h_4 \quad (15)$$
$$q_{Ch} = q_{Ch1} + q_{Ch2} = h_5 - h_2 \quad (16)$$
$$q_C = h_6 - h_1 \quad (17)$$
$$w_P = h_2 - h_1 \quad (18)$$
$$w_t = h_5 - h_6 \quad (19)$$
$$w_u = w_t - w_P = q_{Ch1} + q_{Ch2} - q_C \quad (20)$$

The yield is calculated as follows:

$$\eta = \frac{w_u}{q_{Ch}} \quad (21)$$

By replacing equations (16) and (17) in the expression of the yield, we obtain:

$$\eta = \frac{h_5 - h_2 - (h_6 - h_1)}{h_5 - h_2} \quad (22)$$
$$\eta = \frac{h_5 - h_2 - (h_6 - h_1)}{h_5 - h_2 + h_1 - h_1} \quad (23)$$
$$\eta = \frac{h_5 - h_6 - (h_2 - h_1)}{h_5 - h_1 - (h_2 - h_1)} \quad (24)$$

With:

$$w_P = h_2 - h_1 = v.dP \quad (25)$$

$v$ : Mass volume.

This results in the final expression of the output:

$$\eta = \frac{h_5 - h_6 - v.dP}{h_5 - h_1 - v.dP} \quad (26)$$

Our contribution is primarily to study the influence of pressure on the performance of the installation and then to vary the temperature of overheating to evaluate its effects.

• Two methods can be used to calculate the various thermodynamic parameters: T, P, v, h and s:

- Graphical method: use of Mollier (h, s), Clapeyron (P, v) and enthalpic (T, h) diagrams;
- Analytical method: use of thermodynamic properties tables of liquid water, saturated liquid, wet, saturated steam and superheated steam.

We privileged to work with the tables of the thermodynamic parameters (analytical method) for their precisions.

➢ Working hypotheses

The choice of working pressure varies between:

- 1 to 7 bar for low pressure,
- 10 to 30 bar for high pressure
- the temperature of overheating varies between 200 and 540 ° C.

The temperature range is required, by the configuration of the solar concentration facility; whereas the pressure margin depends essentially on the capacities of the elements of the thermodynamic installation. To reduce both the investment costs and the complexity of the installation; we choose simple and efficient equipment that satisfies the pressure requirements mentioned previously, replacing the technological components of the installation (pump and turbine) with large morphologies and high costs.

➢ **Parameter calculation mode**

• **For the RANKINE cycle**

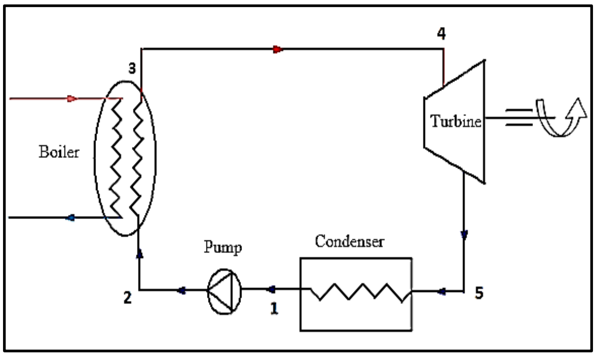


**Figure 7.** Schematic diagram of the RANKINE cycle

The different thermodynamic parameters of each point in the RANKINE cycle are determined, these parameters are tabulated in the thermodynamic tables of the water for the resolution of the yield equation (13).

Let us treat the cycle operating with 2 bars as low pressure and 10 bars as high pressure, as shown in the following figure (8).

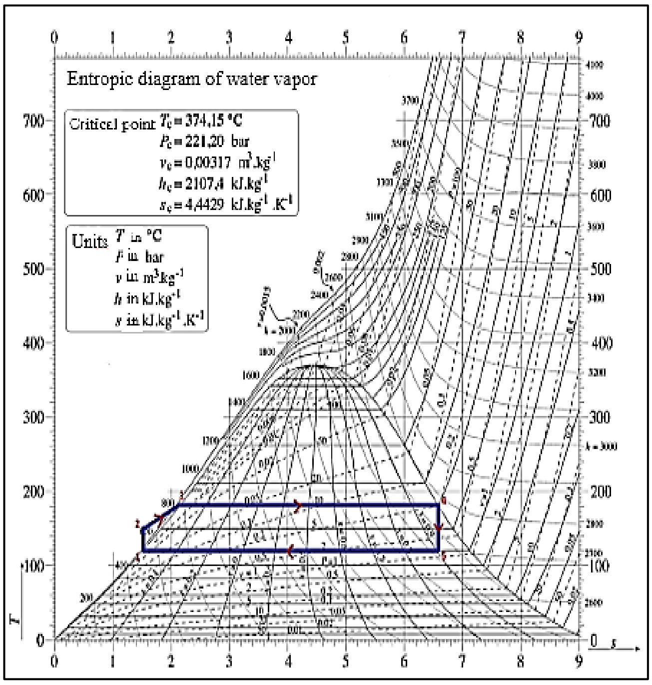


**Figure 8.** RANKINE cycle between 2 and 10 bar

**Point 1 :**

$$\begin{cases} P_1 = 2 \text{ bars} \\ x_1 = 0 \end{cases} \xrightarrow{From\ T.V.S} \begin{cases} T_1 = 120{,}2\ °C \\ h_1 = 504{,}7 \text{ kJ/kg} \\ v_1 = 1{,}0605\ 10^{-3} m^3/kg \\ s_1 = 1{,}5301 \text{ kJ/(kg. K)} \end{cases}$$

**Point 2 :**

$$\begin{cases} P_2 = 10 \text{ bars} \\ s_1 = s_2 = 1{,}5301 \text{ kJ/(kg. K)} \end{cases}$$

**Point 3 :**

$$\begin{cases} P_3 = 10 \text{ bars} \\ x_3 = 0 \end{cases} \xrightarrow{From\ T.V.S} \begin{cases} T_3 = 179{,}9°C \\ h_3 = 762{,}81 \text{ kJ/kg} \\ s_3 = 2{,}1387 \text{ kJ/(kg. K)} \end{cases}$$

**Point 4 :**

$$\begin{cases} P_4 = 10 \text{ bars} \\ T_4 = 179{,}9\ °C \end{cases} \xrightarrow{From\ T.V.S} \begin{cases} h_4 = 2778{,}1 \text{ kJ/kg} \\ s_4 = 6{,}5863 \text{ kJ/(kg. K)} \end{cases}$$

**Point 5 :**

$$\begin{cases} P_5 = 2 \text{ bars} \\ T_5 = 120{,}2°C \\ s_5 = s_4 = 6{,}5863 \text{ kJ/(kg. K)} \end{cases}$$

Calculation of $x_5$ to calculate $h_{5:}$

$$x_5 = \frac{s_5 - s_1}{s_v - s_1},$$

avec

$s_v = 7{,}1271$ kJ/ (kg.K): entropy of saturated steam

$$\text{AN : } x_5 = \frac{6{,}5863 - 1{,}5301}{7{,}1271 - 1{,}5301}$$

$$x_5 = 0{,}9034$$

$$h_5 = x_5\,(h_v - h_1) + h_1,$$

avec

$h_v = 2201{,}9$ kJ/kg: saturated vapor enthalpy

$$\text{AN : } h_5 = 0{,}9034(2201{,}9 - 504{,}7) + 504{,}7$$

$$h_5 = 2493{,}9428\ kJ/kg$$

Performance calculation:

$$\eta = \frac{h_4 - h_5 - v.dP}{h_4 - h_1 - v.dP}$$

AN:

$$\eta = \frac{(2778{,}1 - 2493{,}9428).10^3 - 1{,}0605 .\ 10^{-3}.(10-2).10^5}{(2778{,}1 - 504{,}7).10^3 - 1{,}0605 .\ 10^{-3}.(10-2).10^5}$$

$$\eta = 12{,}4\ \%$$

- **For the HIRN cycle**

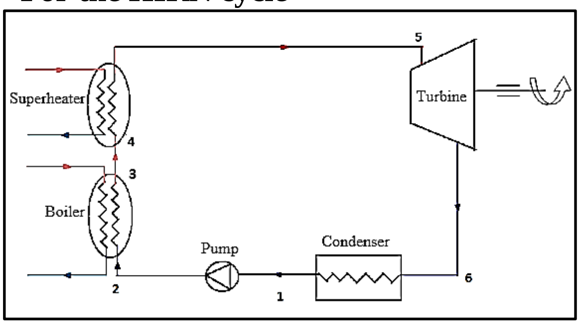


**Figure 9.** Schematic diagram of the HIRN cycle

By the same method as the RANKINE cycle, the different thermodynamic parameters of each point in the HIRN cycle are determined; these parameters are tabulated in the thermodynamic tables of water for the resolution of the equation of yield (24).

By way of example, let us treat the cycle operating with 2 bars as low pressure and 10 bars as high pressure at a temperature of overheating of 400 ° C, figure (10):

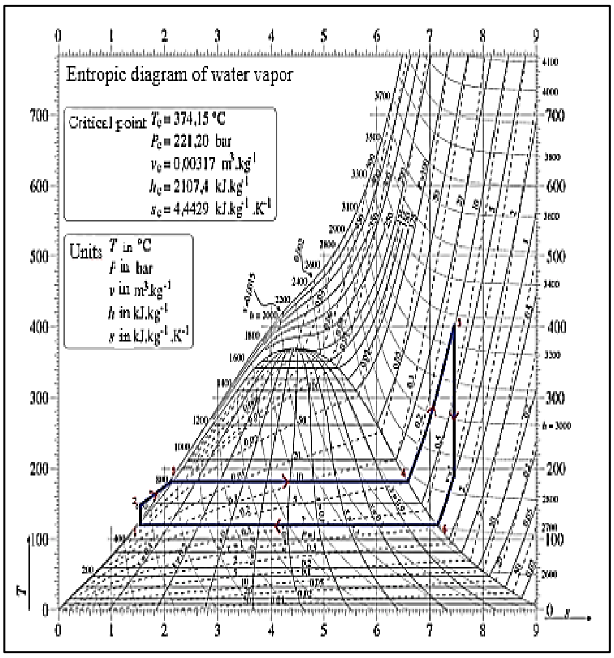


**Figure 10.** HIRN cycle between 2 and 10 bar at 400 ° C

By the same method of RANKINE, one calculates the parameters of the various points and the yield:

$$\eta = \frac{h_5 - h_6 - v.dP}{h_5 - h_1 - v.dP}$$

AN:

$$\eta = \frac{(3263{,}9 - 2986).10^3 - 1{,}0605 .\ 10^{-3}.(10-2).10^5}{(3263{,}9 - 504{,}7).10^3 - 1{,}0605 .\ 10^{-3}.(10-2).10^5}$$

$$\eta = 15{,}2\ \%$$

IX. **Simulation**

**a. Work constraints**

- ***Low pressure:***

The low pressure in the condenser, which is that of the outlet of the turbine, is equal to the saturation pressure of the fluid at the condensation temperature.

**b. Simulation of the RANKINE cycle**

- Constant $P_H$:

To study the influence of the low pressure in the RANKINE cycle on its efficiency, we keep a constant high pressure and we vary the low pressures, by the same calculation method quoted in the previous example, the results are illustrated by curves below:

- **Influence of low pressure**

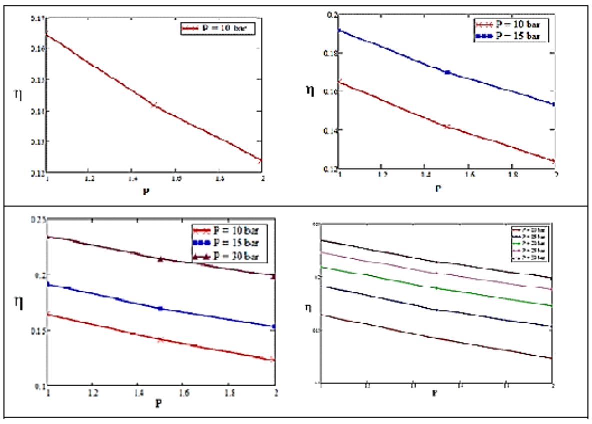


**Figure 11.** Variation of the yield as a function of the low pressures for different high pressures.

**c. Simulation of the HIRN cycle (temperature variation)**

- **Influence of low pressure ($P_B$)**
- Constant $P_H$:

To study the influence of the low pressure as well as that of the overheating temperature in the HIRN cycle on its efficiency, the high pressure is fixed and the low pressures and the temperature of overheating are varied, using the same method of calculation presented in the calculation example (HIRN cycle), the results are illustrated by the curves below:

***a. For PH = 10 bar***

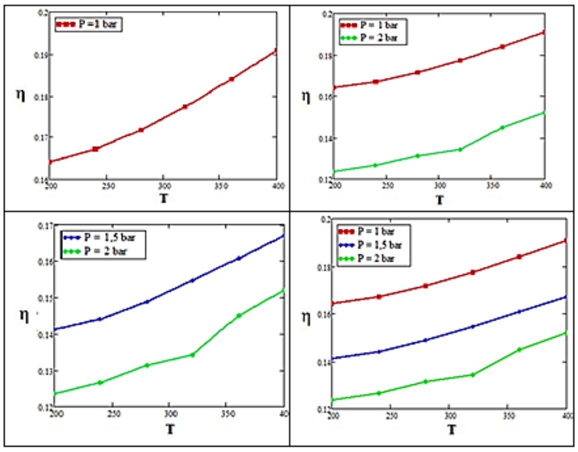

**Figure 12.** Variation of the yield as a of the temperatures for different low pressure ($P_H$ = 10 bar)

### b. Interpretation of graphs

#### *i. RANKINE cycle*

Figure (11) show the variation of the yield as a function of the pressures.

This part (figure (11)) consists in studying the influence of the choice of the low pressure on the performances of the RANKINE cycle, to clarify and value our results we have established our study with several constant values for the high pressure.

❖ In the first analysis,

- Figure (11), we chose a high pressure of 10 bar to see the influence of the low pressure (it was varied from 1 to 2 bars). We have noticed that with the increase of the latter, the return evolves inversely.

The same analysis with the values 15, 20, 25 and 30 bar, allowed us to note the same results, the yield is inversely proportional to the variation of the low pressure. By comparing the graphs obtained between them, we notice that at higher pressures, the yield tends to rise. The graphs in Figure (11) allowed us to compare each yield with all the others according to the low pressures chosen for the study.

#### *ii. HIRN cycle*

Figures (13) show the direction of the variation of the thermal efficiency as a function of the temperature of the superheat for an installation working according to the improved cycle of HIRN (cycle with overheating).

Our study consists in studying the influence of the low-pressure as a function of the overheating temperature on the performances of the HIRN cycle. Systematically,

❖ In the first part,

We chose a fixed value of the high pressure at 10 bar. The superheat temperature was varied from 200 to 400 ° C following three values of the low pressure1, 1.5 and 2 bar as illustrated by Figures (12).

The results presented in the graphs of figure (12) clearly show the evolution of the yield as a function of the overheating temperature. The higher the temperature, the better the cycle.

We notice that with the increase of the low pressure the yield is decreasing. This result is similar to that obtained for the theoretical RANKINE cycle.

## X. Conclusion

This work consisted in modifying the solar concentration thermal installation and changing the thermodynamic parameters in order to study their influence on the efficiency of this installation both following the RANKINE cycle and following that of HIRN.

The parametric analysis of the operation of the installation by highlighting the direction of the variation of the thermal efficiency as a function of the low pressure for a machine working according to the two cycles gave us the following results:

- In the RANKINE cycle, after simulating several cases of pressure evolution, we conclude:

a- That the efficiency is inversely proportional with the elevation of the low pressure.

b- Depending on the pressure difference or when increasing the pressure ratio, the performance is better.

In addition, it is proposed to increase the compression and expansion ratio in the next thermodynamic installations, within the technical and economic limits.

In the HIRN cycle, we studied the influence of the two thermodynamic parameters (temperature and pressure). After having simulated with several changes concerning the temperature of overheating, the low pressure, the results were similar to those found previously:

a- The efficiency and directly proportional to the increase of the temperature of overheating,

b- It is inversely proportional with the elevation of the low pressure.

Our suggestions for future thermodynamic implantations are to increase the compression and expansion ratio as well as to raise the temperature of overheating within the operating limits.

In order to perfect the operation of a solar thermal installation and in the case where the investment and quite expensive, we can afford to add another turbine, after they are heated at the exit of the first turbine (HIRN with reheat) which relaxes the vapors. This will allow us to extract more useful work, without reaching very high temperatures that increase the risk of damaging turbines, in other words, reducing the life of the turbines and the incessant demand for maintenance.

More tests, examinations and specifically advanced studies can be done to verify and clarify the behavior of thermal performance after the design of such geometric changes on the thermodynamic installation, as well as other writings of economic, financial, ecological interests. and environmental will have the opportunity to be updated in order to better understand the usefulness of such achievable improvements on the operating systems of solar energy in particular and all renewable energy easily and abundantly exploitable in general.

This work provides a global idea of concentrated solar power plants, through the ears and its evolution through the centuries.

The coming decades will more than likely see the creation of a large number of Fresnel, parabolic, parabolic, and solar tower concentrators. The costs will be remarkably reduced and it is possible that government incentives for such systems become usefully solicited.

In the medium and long term, concentrating systems will contribute significantly to the objectives of reducing $CO_2$ emissions and the development and energy supply problems of deserted regions.

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