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Modeling and Simulation of Central Tower Receiver (CTR) Plant with Direct Storage System

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Abstract: *In this paper, simulation of a 10MW central tower receiver (CTR) type solar thermal plant with thermal storage system is presented. A two-tank direct method is used for the thermal energy storage. The use of storage system greatly improves the system's ability to provide power at a constant rate despite significant disturbances in the amount of solar radiation available. It can also shift times of power generation to better match times of consumer demand. The present study, building, results, and analysis of the plant model are conducted with Simulink tools in MATLAB program. The simulation results are presented by some days of the summer and winter periods during the year. This model shows how system behavior is affected depending on the available solar thermal power at the tower receiver throughout the day and the effect of the insufficient mass (856764.1529 kg) and the sufficient mass (6586912.534kg) of molten salt.*

Key Words: *Central Tower Receiver (CTR), Solar Thermal Power, Thermal Storage System, Two-tank Direct Method, Mass of Molten Salt,*

1. INTRODUCTION:

The use of fossil fuels has produced large amounts of air pollution due to the release of harmful gases as combustion byproducts. Additionally, power plants often release large amounts of waste heat to the environment. This can lead to thermal pollution in rivers and lakes causing harm to many forms of plant and animal life [1]. Recently, solar energy as a kind of clean and renewable energy source has been drawing more and more attention due to the shortage and pollution of fossil fuels, especially in electricity generation.

Concentrated solar power (CSP) and photovoltaic (PV) are two leading solar technologies in the power generation industry. PV collectors are capable of directly converting solar radiation into electricity. On the other hand, CSP collectors convert solar radiation into thermal energy. This thermal energy at a high temperature is then transferred to a working fluid to produce electricity through a conventional thermodynamic cycle [2].

The central tower receiver (CTR) is known as one of the most promising technologies for producing solar electricity due to the high temperatures reached, resulting in high thermodynamic performances [3]. And, CTR is also an attractive method to achieve tremendously huge power and high concentration of solar irradiance for electricity generation or thermal processes [4].

CTR plant generates electric power from sunlight by focusing concentrated solar radiation on a thermal receiver mounted at the top of a tower. The heat transfer fluid (HTF) at minimum operating temperature is pumped from a cold storage tank through the receiver where it is heated to its maximum operating temperature and then on to a hot storage tank. When power is needed from the plant, the HTF is pumped to a steam generating system that produces superheated steam for a conventional Rankine cycle turbine/generator system. From the steam generator, HTF is returned to the cold storage tank where it is stored and eventually reheated in the receiver [5]. The schematic diagram of a simple two tanks molten salt CTR plant is shown in Figure 1.

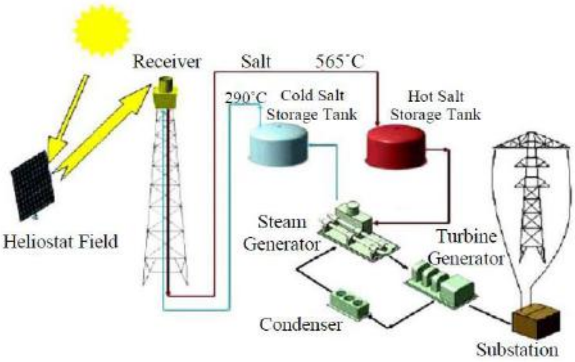


Figure 1. A Simple Schematic Diagram of a Central Receiver Type Solar Thermal Plant [6]

2. OVERVIEW OF THE PROPOSED SYSTEM:

The proposed system is a 10MW central receiver type CSP plant. In this plant, heliostat field layout with radial staggered pattern is considered and composed by 1197 heliostats. Each heliostat is a mobile 121 m^2 reflective surface mirror that concentrates solar radiation on an external receiver, through which the HTF flows while it absorbs heat, placed on top of a 70 m tall tower. These data are calculated by using the equations indicated in [3].

The thermal energy storage system modeled in this work uses the two-tank-direct configuration where the heat transfer fluid also acts as the energy storage medium. This requires two separate tanks, but eliminates the need for an additional heat exchanger to transfer heat from the collection HTF to the storage medium. The fluid is stored at its lower temperature in a cold tank, heated in the solar collector field, and then stored at an elevated temperature in the hot tank [7]. The detailed parameters of the base case 10 MW plant are listed in Table 1.

Molten salts are the only commercial storage medium nowadays for storing energy during extended periods of time. The molten salt chosen was a nitrate salt that is composed of 40% KNO_3 and 60% $NaNO_3$. The desired characteristics for molten salts are low vapor pressure, high density, low chemical reactivity, moderate specific heat and low cost [8].

Table 1. Properties of the base case central receiver parameters

Properties	Value
Plant Rating	10 MW
Rankine Cycle Efficiency, $\eta_{Rankine}$ [9]	40%
Receiver Efficiency, η_{rec} [6]	94%
Specific Heat Capacity of Molten Salt, C_p [10]	1516.53 J/kgK
Density of Molten Salt, ρ_{ms} [10]	1818.11 kg/m^3
Maximum Operating Temperature of Molten Salt [11]	565˚C
Minimum Operating Temperature of Molten Salt [11]	290˚C
Required Thermal Power for Power Block, Q_{req}	25 MW_{th}

3. MODEL DESCRIPTION:

The simulation model for CTR plant is built using MATLAB software tool called Simulink and is shown in Figure 2. The mass flow m_1 is the molten salts flow rate that goes out of the hot tank and passes through the steam generator for providing the steam in order to produce electrical power in the turbine and then continues flowing to the cold tank from the steam generator. The mass flow m_2 is the molten salts flow rate that goes out of the cold tank into the tower receiver for warming up and then continues towards the hot tank. In order to design the heat transfer fluid mass flow, the following equation is used [12].

$$m = \frac{Q_{tr}}{C_p \Delta T} \qquad (1)$$

where, Q_{tr} = thermal power at the tower receiver, C_p = specific heat capacity of HTF fluid

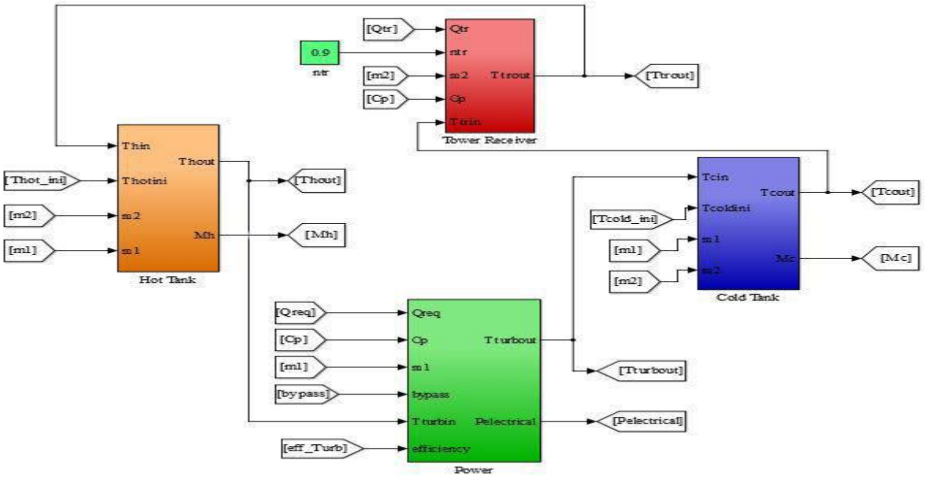


Figure 2. Simulink Model of the CTR Plant with Direct Storage System

3.1 Tower Receiver Subsystem

In CTR plant, the receiver is used for receiving sunlight from the heliostat field to raise the working fluid temperature to the desired temperature. The receiver design has been optimized to absorb a maximum amount of solar energy while reducing the heat losses due to convection and radiation. The molten salts, is pumping from the cold storage tank by using electrical pump. The molten salts then enters the tower receiver to heat from minimum operating temperature to a maximum operating temperature.

The formula which describes the tower receiver subsystem is defined as follows [13]:

$$T_{tr,o} = \frac{Q_{tr}\eta_{tr}}{m_2 C_p} + T_{tr,i} \tag{2}$$

where, $T_{tr,o}$ = outlet temperature of tower receiver , η_{tr} = receiver efficiency, $T_{tr,i}$ = inlet temperature of tower receiver

Figure 3 shows the detail model the tower receiver subsystem which provides the modeling based on the equation (1).

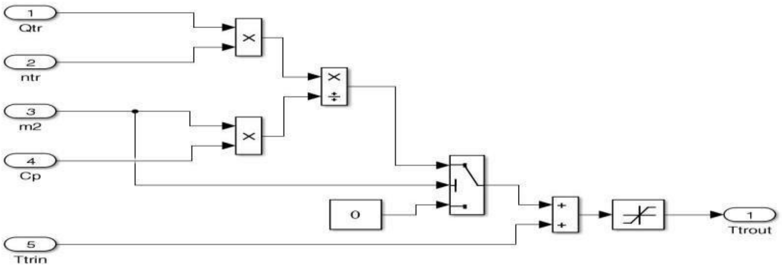


Figure 3. Tower Receiver Subsystem for Outlet Temperature Modeling

3.2 Storage Subsystem

Reliable energy storage method is a crucial element in successful year-round operation of a thermal solar power plant. Using molten salt as a storage medium, the technical realization can be distinguished by direct or indirect storage systems. Indirect thermal storage systems have a different heat transfer fluid in the solar field compared to the storage media. Due to the use of only one heat transfer fluid, direct thermal energy storage has significant cost advantages compared to indirect storage systems. The storage system is consisted of two heat reservoirs which are called hot and cold storage tanks.

Hot storage tank is the main storage tank used in the storage system. Working fluid at its maximum operating temperature is flows from the tower receiver to this tank. Cold storage tank is the complementing storage tank used in the storage system. It is very similar to the hot storage tank in its operations, equations, and Simulink model. To determine the mass balance of this tank as a function of the mass flows, the following equation is used [13].

In order to model and define the equation of the storage subsystem, it is necessary to determine the mass balance of this tank as a function of the mass flows [13].

$$M_h(t) = \int_{t_o}^{t} m_2 - m_1(t)dt + y_o \quad , \quad M_c(t) = \int_{t_o}^{t} m_1 - m_2(t)dt + y_o \tag{3}$$

where, t = upper saturation limit, t_o = lower saturation limit, y_o = initial condition for both tanks

Once define the mass balance, it is necessary to define an initial working operation temperature for both tanks ($T_{h,ini}$ & $T_{c,ini}$) of 290°C as the minimum operation temperature of the HTF and an energy balance of the tank. It is admitted that $T_{tr,o}$ (outlet temperature of the tower receiver) is going to be the $T_{h,i}$ (inlet temperature of molten salts in the hot tank). The inlet temperature of the cold tank ($T_{c,i}$) is equal to the outlet temperature of the turbine ($T_{tur,o}$). The outlet temperature for both tanks is computed as follows [13] and their math operation models are shown in Figure 4:

$$T_{h,o} = \frac{m_2(T_{h,i} - T_{h,ini})}{M_h(t)} + T_{h,ini} \quad , \quad T_{c,o} = \frac{m_2(T_{c,i} - T_{h,ini})}{M_c(t)} + T_{c,ini} \tag{4}$$

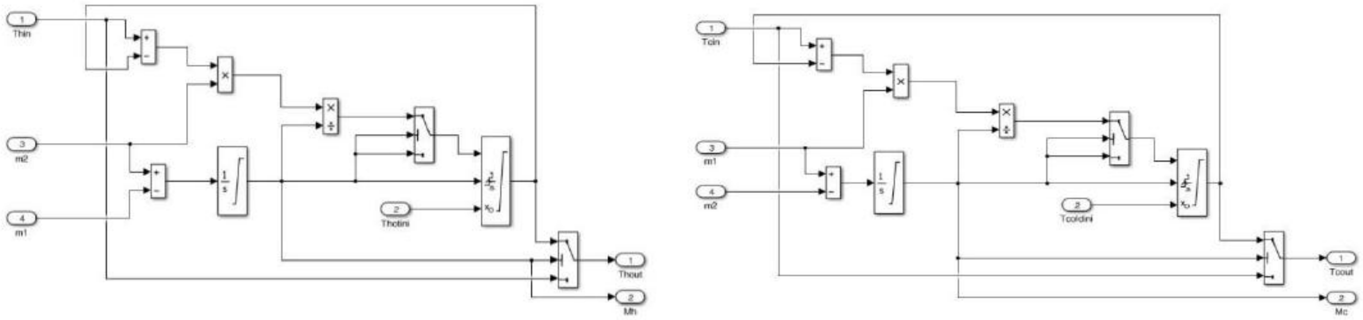


Figure 4. Simulink Model of the Outlet Temperature of the Both Tanks

3.3 Electric Generation Subsystem

This subsystem includes the turbine outlet temperature ($T_{tur,o}$) and the power generation ($P_{tur,o}$). It is assumed that the outlet temperature of molten salt in the hot tank ($T_{h,o}$) is equal to the inlet temperature of molten salts into the turbine ($T_{tur,i}$) because the vapor cycle, which includes the steam generation. The outlet temperature of the turbine is defined as follows [13]:

$$T_{tur,o} = T_{tur,i} - \frac{Q_{req}}{m_1 C_p} \tag{5}$$

The above equation (5) is presented in Figure 5 as Simulink model to build the electric generation subsystem.

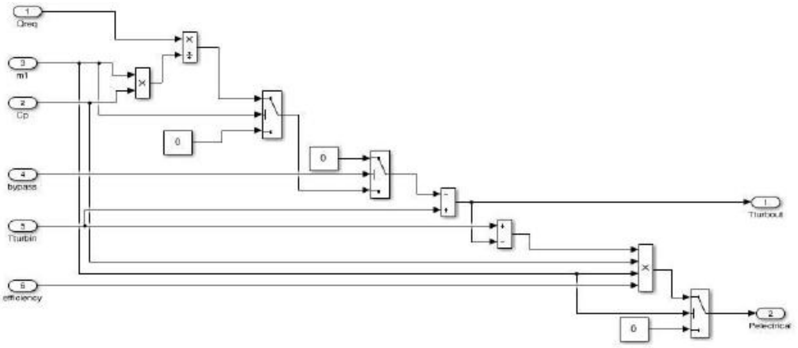


Figure 5. Electric Generation Subsystem Designed with Simulink

In order to calculate the power output power released by the turbine ($P_{tur,o}$), also known as power demand (P_{demand}), as a function of the solar thermal power required (Q_{req}) and the turbine Rankine cycle efficiency ($\eta_{Rankine}$), the following equation is used [13].

$$P_{turb,o} = Q_{req}\ \eta_{Rankine} \tag{6}$$

The model of this equation is presented below in Figure 6 where the condition for bypass = 0 and $m_1 > 0$ are defined on the equation block of Simulink in order to obtain $P_{tur,o}$.

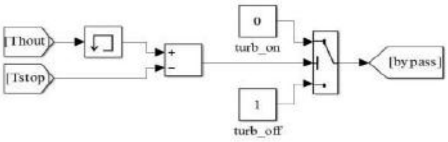


Figure 6. Simulink Model for Calculation of $P_{tur,o}$ under Control Conditions

4. RESULTS AND DISCUSSION:

Theoretical results of the plant are described in this section. The simulation parameters are defined with a fixed time step of 0.5 sec and a simulation time of 86400 sec, which are the total seconds of the days.

4.1 System without Effect of Mass of Molten Salt

Running the simulation for the one day of the year, April 15, it is observed that both tanks are half filled initially. Mass of molten salts from the hot tank flows through the steam generator at a constant rate to produce the constant electrical power output (10MW) and then continues flowing to the cold tank while the mass flow rate m_2 varies depending upon the available solar radiation, as shown in Figure 7.

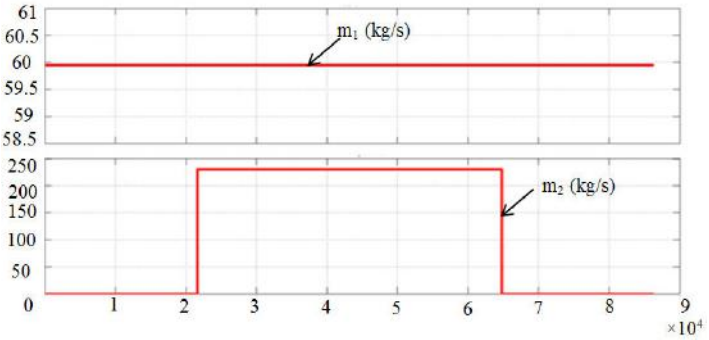
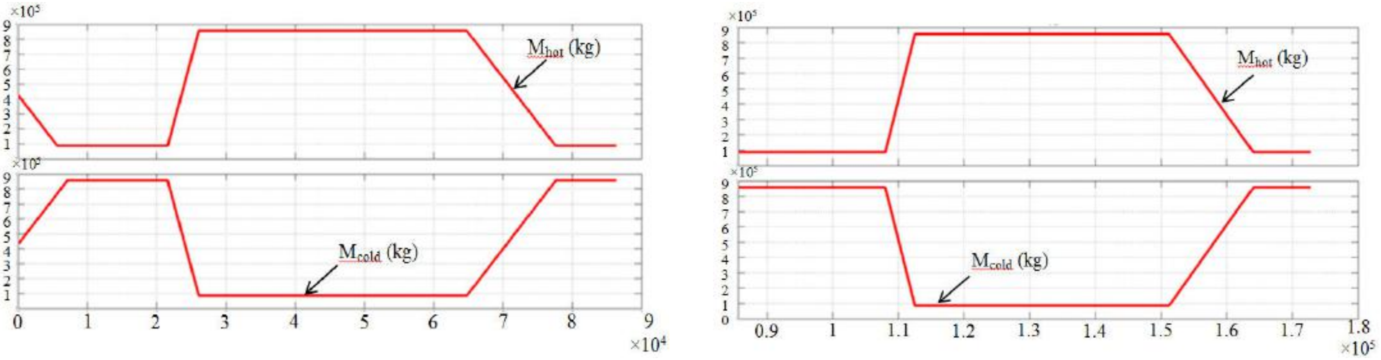


Figure 7. Mass Flow Rate Variations of the CTR Plant during April 15

By simulating these mass flow rates, the cold tank is getting to its maximum mass and the hot tank to its minimum mass during the first six hours of the day. When solar variation is available, the process is proceeding afterwards in a cycle way as shown in Figure 8 (a).

Between 1h - 6h and 18h - 24 h (the hours without radiation) the cold tank is full with molten salts and the hot tank gets to its minimum mass. On the other hand, in the period 6h - 18h (when radiation is available) the mass of molten salt in the cold tank decreases to its minimum mass and the hot tank is full. For the cold and hot tanks, it is observed that they are filled and minimum mass during 6.5 hours of the day respectively. This simulation was made essentially to show the initial situation in both tanks and the cyclic process, being also observed that the mass of each tank have the same opposite behavior along the year during the different states of operation and in different days of the year as seen in Figure 8 (b). In this case, the simulation applies for a summer day, 16th April.

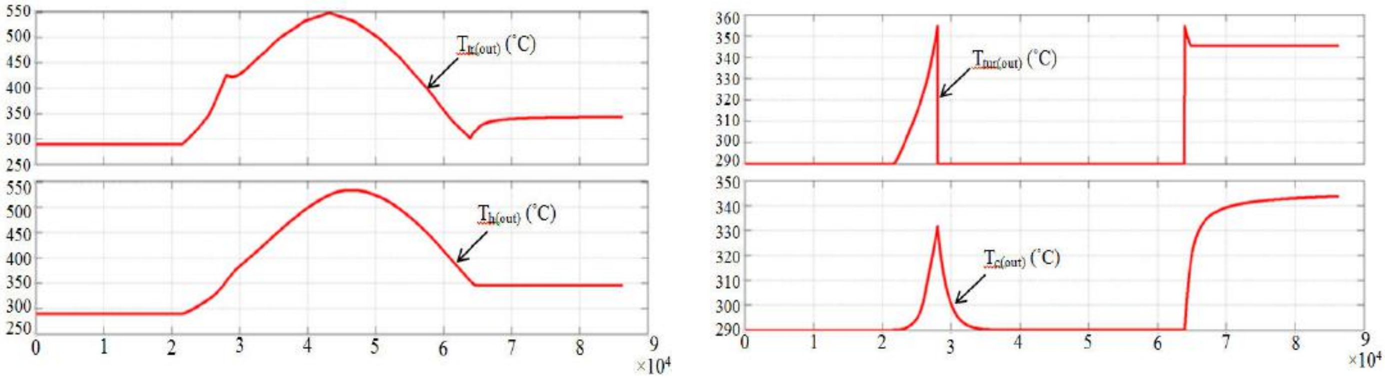


(a) for April 15 (b) for April 16

Figure 8. Cold and Hot Tank Masses and Their Variations

In the beginning of the second day, the cold tank is full and the hot tank is getting minimum mass of molten salts, according to what occurred during the previous day, so the mass of each tank will have this behavior every day along the year. The day right after will continue following the same pattern, and the mass in each tank which will always be $M_c = 856764.1529$ kg and $M_h = 85676.41529$ kg.

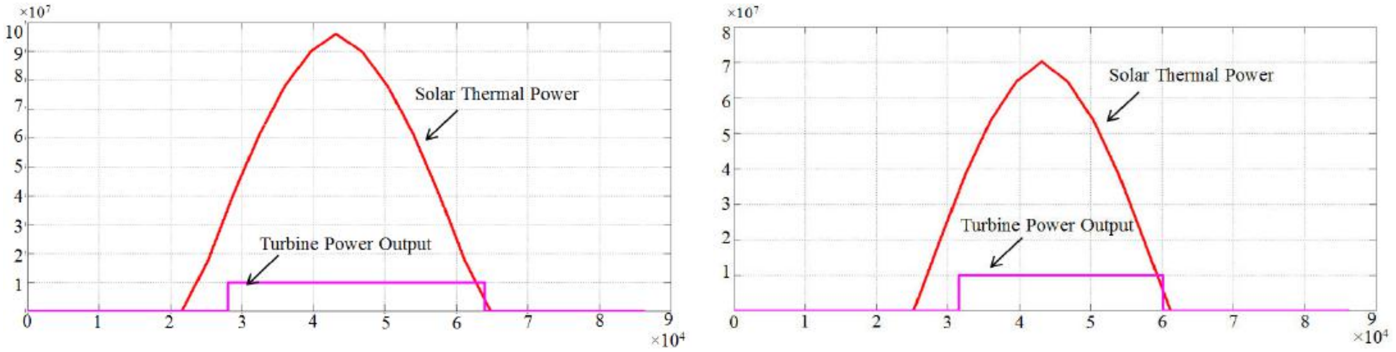
After analyzing the mass on the storage system, the variations of temperature of the CTR plant is studied. This simulation was made for the total hours of the year, and it can be seen that the limit operation temperatures of the CTR plant referred before (between 290˚C and 565˚C because of the molten salts freezing point and material resistance) are being accomplished. The temperature profile for the tower receiver agrees with the radiation available during the day. The hot tank reached higher temperatures according also the highest levels of irradiation, so the highest energy at the tower receiver and more capacity to heating the molten salts, as shown in Figure 9 (a). On the other hand, there were sudden changes in the turbine outlet temperature during the sunrise and sunset hours. The outlet temperature of the hot tank also changed depending on the turbine outlet temperature, as shown in Figure 9 (b).



(a) for Tower Receiver and Hot Tank (b) for Turbine and Cold Tank

Figure 9. Temperature Variations of the CTR Plant during April 15

It is observed that the temperature of the cold tank never goes under 290˚C and the maximum temperature reached by this tank is around 345˚C because it is receiving the hotter molten salts that are heated up on the tower receiver and then released to the hot tank and steam generator where finally were sent back again to the cold tank. The next plot was made the electrical power output provided by this plant regarding the amount of solar thermal power received, as presented in Figure 10 (a). The result observed that during this simulation shown a clear correlation between the solar thermal power available at the tower receiver and the turbine power output. The power controller keeps the constant power output at its set point. Early in the day, the energy is harvested by storing excess hot molten salt in the hot storage tank. Upon this simulation, it can notably be seen a decouple between the electrical power produced and the solar thermal power, which means that when the solar radiation has variations, the electrical power output is not depending strongly on those variations, which is caused by the inertia of the storage system. Besides when the thermal power is starting to decrease, the nominal power output is maintained and the storage system is providing a more stable electrical production.



(a) for April 15 (b) for December 15

Figure 10. Turbine Power Output and Solar Thermal Power

Another analysis was made for the winter time, in the month of December, as shown in Figure 10 (b) in order to compare with the summer results. The most significant differences are the lower solar thermal power due to the lower solar radiation. Meanwhile, it is still observed decouple and an inertia of the system, but no during longer periods as the summer.

An obvious explanation for the short autonomy is the fact that the mass of molten salt in each tank is insufficient. When the solar thermal power is starting to increase the system doesn't produce electricity simultaneously because of the storage system which has some inertia and the electrical production to the solar thermal power and consequently to the solar radiation.

4.2 System with Effect of Mass of Molten Salt

An additional analysis to evaluate the influence of molten salts mass in the autonomy and decoupling observed was then proposed.

Heat storage capacity of molten salt [14] = 2710 kJ/m^3°C

Receiver output temperature [11] = 565˚C

Receiver input temperature [11] = 290˚C

Temperature rise in the receiver = 565˚C – 290˚C = 275˚C

Energy absorption per m^3 of molten salt = 2710 kg/m^3 × 275˚C = 745.25 MJ/m^3

No of storage hours to be considered, $h_{storage}$ = 15 hrs

Total energy required in storage = $Q_{total} \times h_{storage} = 50 \times 15 \times 3600 = 2700000$ MJ

Required molten salt volume, $V_{tank} = \dfrac{2700000 \text{ MJ}}{745.25 \text{ MJ/m}^3} = 3622.945 \text{ m}^3$

Take storage tank diameter, d = 20 m

Storage tank height, $h = \dfrac{V_{tank}}{\pi \times r^2} = \dfrac{3622.945}{\pi \times 10^2} = 11.532$ m

Required amount of molten salt for both tank, $M_c = M_h = \rho_{ms} \times V_{tank} = 1818.11 \times 3622.945 = 6586912.534$ kg

The required mass of molten salt for cold and hot tanks must be 6585912.534 kg. This new mass is nearly eight times bigger than the previous mass and the variations of this new mass for April 15 are shown in Figure 11.

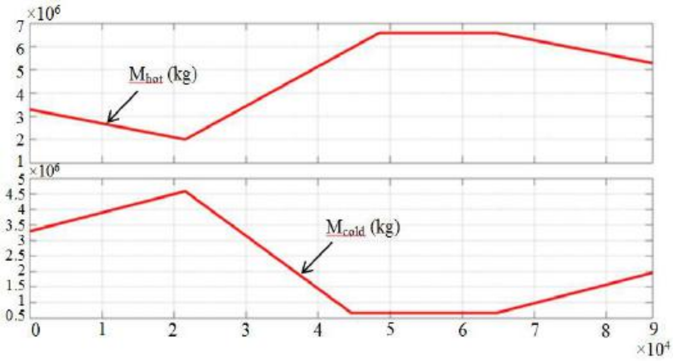
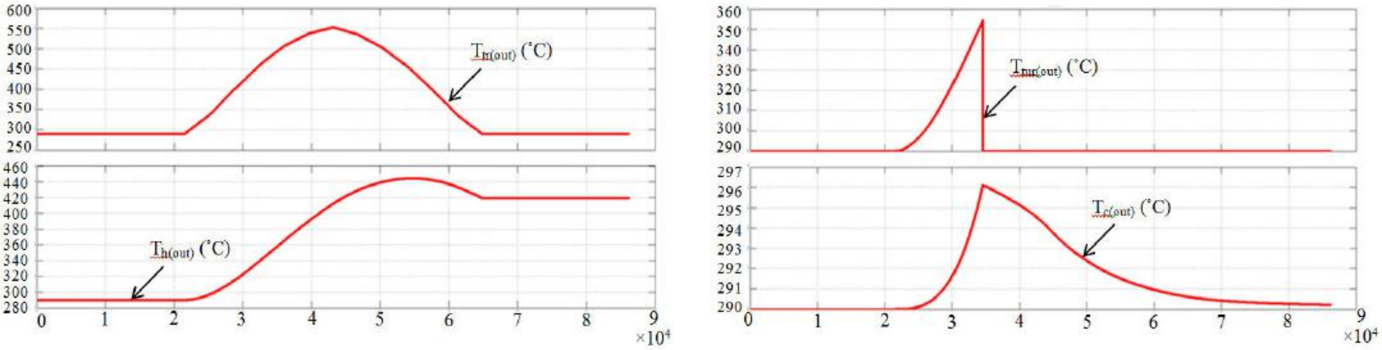


Figure 11. New Masses and Their Variations of Cold and Hot Tank during April 15

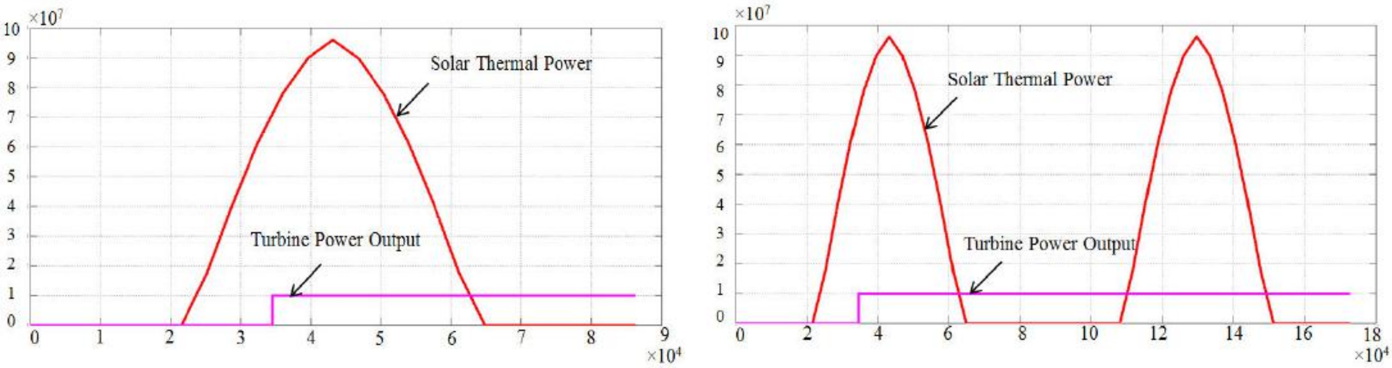
In Figure 12 (a) and 12 (b), during the day light, the control system on the flow rate of molten salts to the receiver make the temperature of the molten salts at the tower receiver outlet reach around its desired temperature 565˚C. This outlet temperature is the inlet temperature of the hot tank in addition to the cold storage tank outlet temperature around its desired temperature 290˚C. This achieved during every day in the year. But the first day of the plant operation has a specific temperature change.



(a) for Tower Receiver and Hot Tank (b) for Turbine and Cold Tank

Figure 12. Temperature Variations of the CTR Plant during April 15 (Effect of Mass of Molten Salt)

The next simulation was also run over the total seconds of the day in order to verify that the plant can generate steam at a constant rate for several hours after sunset, as presented in Figure 13 (a). Comparing this new simulation results to the initial graph obtained with a lower mass in Figure 10 (a), it is observed that the number of hours to produce the electrical power output is longer than that of previous one, although is notably seen during the first six hours of the plant operation that the power output is zero. But this type of the plant operation is only for the first day because there is sufficient mass of molten salts to absorb excess thermal energy efficiently during solar radiation. This allows the plant to continue to generate constant electrical power output for several hours without radiation. In order to demonstrate this situation, Figure 13 (b) shows the behavior of the plant operation during two days of the month, April 15 and 16.



(a) for April 15 (b) for April 15 and 16

Figure 13. Turbine Power Output and Solar Thermal Power (Effect of Mass of Molten Salt)

It is verified that the plant doesn’t start the production of electrical power production on the first six hours because there is a big inertia. This is happening because the molten salts take some hours to reach the desired minimum operation temperature for generating vapor and then to produce electrical power. Initially the temperatures at both tanks are defined for 290˚C and they need time to reach the desired 565˚C. So, considering that the plant starts its operation during the first day of the year and that the radiation is lower is normal that this process takes some time especially when the mass to warm up is five times bigger than before, creating a bigger decouple and inertia of the system.

This behavior is provided by the inertia of the storage system and by the higher decouple between the thermal power and the electrical power. It is noticed that the steam turbine runs much more time to produce the electrical power comparing to the initial situation (smaller mass of molten salts) in the same day of the year. This happen because there is a minimum time required to reach the desired temperature of the hot tank, yielding a higher independence of the electrical system compared to the thermal generation system. Meanwhile when there’s no more solar radiation and consequently, no more solar thermal power, the CTR plant is still producing electrical power during several times and having its desired autonomy.

The same examination is done in the next figure, but for a winter period. As a result, Figure 14 shows the one day in December 15 and the performance of the electrical power production and solar thermal power available for this day.

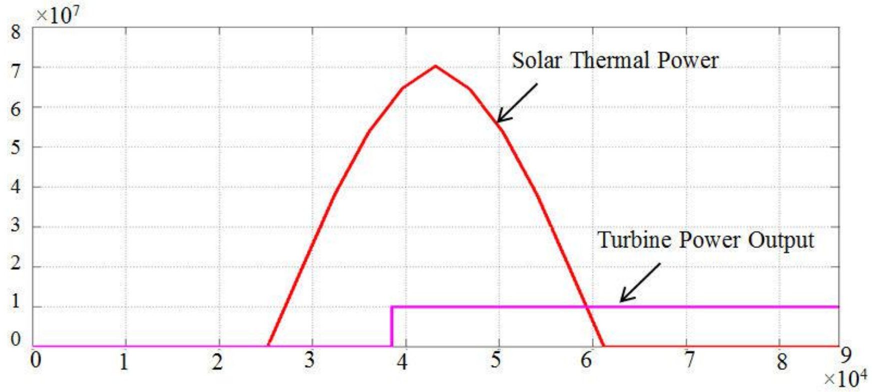


Figure 14. Turbine Power Output and Solar Thermal Power during December 15 (Effect of Mass of Molten Salt)

It is noticed now a bigger difference between the summer and the winter period. In fact, the electrical power production starts later in this day and the solar thermal power is restricted to less hours of the day. In addition, during a winter day it is found that the storage system makes the electrical production totally independent of the solar radiation, and because the mass is bigger, the production starts much later than in the summer, provoking a delay effect.

5. CONCLUSION:

Analyzing all of the those simulation for April 15 and December 15 during the year, it is observed that the number of operation hours of the plant is determined based on the thermal power generation system and the electrical power production system, so it is depending on the available solar radiation of each day. And then, it is also observed that the plant operation has different performance when the mass of molten salt is 856764.1529 kg and when the mass is 6586912.534 kg. The main differences are the number of operation hours of the CSP plant, which are higher when the mass of molten salt is also higher. The autonomy of the plant, which is determined when the available solar thermal power is lower than the electrical production, is raising when the mass of molten salt is about five times bigger, providing also a higher decouple between those two variables, electrical power output and solar thermal power. Apart of the mass variation, the plant has a higher autonomy during a summer period than in a winter period.

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