AIDIC CONFERENCE SERIES
A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/acos

VOL. 11, 2013
Chief Editor: Sauro Pierucci
Copyright © 2013, AIDIC Servizi S.r.l.,
ISBN 978-88-95608-55-6; **ISSN** 2036-5969

DOI: 10.3303/ACOS1311031

Study of Direct Thermal Energy Storage Technologies for Effectiveness of Concentrating Solar Power Plants

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In this paper, numerical comparisons are devised among different direct thermal energy storage (TES) technologies of concentrating solar power (CSP) plants with possible alternatives in design, plantwide control and global economic considerations and therefore, leading the process up to the sustainable power production through the day and night. The first design is based on the conventional direct double-tank thermal energy storage CSP plant, and afterwards, the modification on the design of this plant is proposed. The modification on the plantwide control is followed by recycling the heat transfer fluid (HTF) through the solar field and decreasing the degradation of temperature of the storage in discharge period. In addition, the analogues analysis is performed towards the solutions of the stable behavior on dynamic of the storage and power production. Owing to the fact that the single-tank storage technology eliminates using an extra storage volume in process design, consequently, it decreases the capital cost of the plant, the dynamic design of the single-tank storage technology is presented. Avoiding the greater degradations of the parameters is considered and improved through the heat exchanger trains as a challenging issue in storage technologies along with the plantwide control. In this work, considerations of process control to improve the quality of storage, operational issues, and flexibility related to the selected TES technologies are discussed due to making decisions for optimal control and covering the demanded energy generated by CSP plant.

1. Introduction

Dynamic simulation and improvement in the design and control of the solar power plants might compete with remarkable considerations on enhancement of storing this abundant source along with optimal generation of energy by the means of advanced technologies of thermal energy storages in CSP plants. This is promising to sustain the power generation through the day and night and using it at the later instant. Although, the solar power plants confront the numerous technical and economic problems due to the instability of the source of energy, the storage systems guarantee the stability of generated energy in these plants. In other words, by means of TES system in CSP plants, it is possible to converting the intermittent and instable source to stable energy (Powel et al., 2012). In order to meet the stability in power generation, overall concerns in solar power plant, operability and comparability of conventional storage technologies should be taken into account to prolong and sustain the delivery of this energy to power generation block. The harvesting of energy by appropriate thermal storage technologies is directly connected to produce the high quality steam power. Hence, to control and troubleshooting of perturbations affected by the intermittent source, it is required to design the flexible and controllable intermediate facilities to transfer this unstable energy to stable production for peak demand times (Herrmann et al., 2002; Powell et al., 2011). This research activity is mainly focused on the dynamic simulation of two different TES technology adopted with concentrating solar power plants in order to assess the effectiveness, controllability and flexibility in terms of harvesting and conversion.

Please cite this article as: Ravaghi-Ardebili Z., Manenti F., Nascimento Lima N.M., Zuniga Linan L., 2013, Study of direct thermal energy storage technologies for effectiveness of concentrating solar power plants, AIDIC Conference Series, 11, 301-310
DOI: 10.3303/ACOS1311031

2. Concentrated Solar Power Plants

Solar energy technologies could be categorized in terms of the definition of applied systems. In general, CSP plants are subdivided into following general functional technologies:

1) Concentrating and non-concentrating (with reference to the concentration techniques used to focus the beam into plant);

2) Thermal and photovoltaic (in terms of direct usage from solar energy in PV technologies or store and dispatch it for later applications and,

3) Passive and active (according to thermal storage system variations in its structure, material and heat Transfer fluid) (Cabeza et al., 2012).

2.1 Concentration Technologies in CSP plant

The common technologies in absorption of solar radiation to focus and transfer into the plant are branched into several common classifications, whereas all of them follow the common concept to concentrate the sunlight into a receiver. In general, heat transfer fluids (HTF) flow through the pipelines of concentrators and the temperature of them is increased (Pavlovic et al., 2012). Afterwards, this heated HTF flows down to store in storage tanks. The concentration technologies are well-known as: parabolic troughs, power tower, parabolic dishes (dish stirling) and Fresnel reflectors (Muller et al., 2004).

2.2 Thermal Energy Storage in CSP plant

Thermal energy storage (TES) systems are the potential for CSP plants to increase the effectiveness of the plant. They facilitate the CSP plant to cope with the mismatch between the supply and demand of the energy and stability of the power generation. Common TES systems on CSP plants are typically based on sensible storage systems, latent storage and chemical reaction storage technologies following the materials and application of CSP plant. The concept of the TES plant is based on increasing the temperature of working fluid by increasing the content of its energy. In the case of sensible, the increasing or decreasing the temperature of HTF causes the energy released or absorbed. Latent storage takes occur heat exchanges between phases. It means the energy is released by converting a solid to a liquid, or a liquid to a gas or absorbed in changes of phases vice versa (i.e., liquid to solid or gas to liquid). The other common case TES technology, i.e., chemical reaction, the reversible endothermic reactions is associated to heat storage or discharging by dissociating chemical products. The recovery of the heat takes occur in reverse reaction by synthesis reaction (Gil et al., 2010).

3. Thermal Energy Storage (TES) System

As it is discussed earlier, the TES is an intermediate and critical block of a CSP plant which is provide the possibility to store and dispatch the concentrated solar energy into power block. Heat integration is typically considered only in steady state, whereas the system suffers from vigorous dynamic behavior. Moreover, the TES is conceptually dynamic and therefore, system needs to provide flexibility to collect heat at proper time and deliver it for a later time. Due to this, dynamic simulation is the only methodology to investigate such these systems. The TES concept in CSP plant is structured by transporting the thermal energy with accumulation of HTF into the storage tank (Powell et al., 2011, Yang et al., 2010), based on saving heat energy through the day light – as called *charging time* – and afterward, consuming the stored heat energy through the night – as called *discharging time* – which causes the gradual dropping at the temperature of charged storage until the further charging period. Through the process, heat transfer fluid flows over the solar collector to heat and increasing its temperature before pumping down into the thermal storage tank, store and produce the steam (Vaivudh et al., 2008). The cooled HTF is then pumped back into the cold tank or directly to the collector field to be heated at another time depending on the thermal energy storage technology applied in the plant.

3.1 TES Technologies in CSP plant

Thermal energy storages generally are categorized in terms of applied TES technology and loading method meant to *direct thermal storage* and *indirect thermal storage*. In *direct* systems, the heat transfer fluid acts as the storage medium, simultaneously, whereas, in indirect systems, a storage medium is different from the transferring fluid (Cabeza et al., 2012).The dissimilarity between these technologies is specified according to the location of the thermal storage tank related to the heat exchanger (HEX) block, number of applied utilities and moving devices such as pump and valve, the medium and transfer material *etc*.

3.2 Active and Passive Systems

An active storage system is identified by the forced convection heat transfer into the storage material. The storage medium itself circulates into the storage system and HEX block. Active systems are subdivided into direct and indirect systems, as it explained in earlier section (Cabeza et al., 2012). By definition, active storage refers to storing energy in day time and apply it for later in cloudy days, though passive is extending the use of day light through building design to use more from day light and it charges and discharges a solid medium (Timilsina et al.,2011). Active thermal storage could be designed as a single – or a double -tank system (Vaivudh et al., 2008).

4. Dynamic Simulation, Control and Design Considerations

There are several dynamic simulations, which have been performed to improve and to well-assess the effectiveness of solar plants with design (Calise et al., 2012), numerical solutions (Cheng et al., 2012), economic issues (Cheng et al., 2012) and to monitor (Xu et al., 2012), predict (Xu et al., 2012) and control(Powel et al., 2012) the thermal energy storages. Although numerous works were performed on the storage technologies, few detailed works have been found on the modeling and simulation of entire plant and not specified on the TES assessment in connection with the further units and the related performances in the simulation of the entire CSP plant and the operational effects. In addition, it is not found remarkable works based on well-established commercial dynamic simulators, which are employed for accomplishing the conventional dynamic processes and control issues24. In this work, the dynamic simulation of different technologies of molten salt direct thermal energy storage of CSP plants is presented. To assess the performance of the plant, double-tank storage technology and afterwards, the single-tank storage are simulated. In the following sections, we describe the detailed of each layout with control scheme and operability.

4.1 Direct Double-Tank Storage Design

The following layout (Figure.1) is the conventional double-tank storage applied in solar industrial plants, with highlighting the role of TES in process. The solar radiation is set to the nominal amount of 77MW (Vitte et al., 2012). This is applied based on routine sunny day in summer starting from 7-8 am, afterward, ramping up to constant radiation through the day within 10-12 hours, and sloping down to zero (no radiation) at 7-8 pm. The peak demand hours then starts since the stored energy is used until the charging period (sunrise) of the next day. To consider the detailed description of simulated flowsheet, the following process flow is given. According to Figure. 1, molten salt is supplied to the plant through the start-up line and pumped into the cold storage tank. This line operates only during the start up because no make-up of molten salt is usually needed in the short/medium terms. Once the applicable content of molten salt is provided for demand of process, molten salt from cold tank is driven down to the collector field into the hot storage tank. The collector pipes modelled impose solar energy into the system. This scenario is applied for the typical summer daytime operation and we will refer the section as the *solar line* to Archimede CSP plant (Manenti and Ravaghi-Ardebili, 2013). Through the night, the solar line (the line connecting cold storage tank to hot storage tank via collector field) stops the operation as there is no longer the radiation. However, the *generation line* (the line connecting hot storage tank in cold by means of heat transfer trains) runs continuously through 24 hours under the controlled conditions (different PIDs in the direction) to generate the demanded steam power for standing in-time renewable power supply and match the prospects of industry as above-described scenario. In HEX block of CSP plant, four heat exchangers are placed on generation line to provide the high quality steam for power block. Following the stream (S1) of molten salt from the hot storage, molten salt encounters SECOND SUPERHEATER, FIRST SUPERHEATER, BOILER (boiler is utilized in this chain to provide phase changes and produce the steam for block) and ECONOMIZER, respectively to fulfil the steam generation. Obviously, in this direction, molten salt temperature decreases while steam generates.

In HEX train, the temperature of molten salt is decreased from 550˚C (inlet of HEX block, which is the identical temperature of storage) to 290˚C (in outlet of the HEX block, where is kept the temperature of cold molten salt above its freezing point). Therefore, molten salt flows through collector pipes from cold tank to be heated and then, loaded in the storage tank. In discharging step, heat is drawn from the storage tank into the cold tank. With this design and control scenario process, the system is profited half- day full load storage capacity.

4.2 Rational Layout of Direct Double-Tank Storage Design

The challengeable issue in the design and control structure of double-tank storage CSP plant is controlling the temperature of storage in early hours of the day, while the cold HTF starts to heat up. The matter of fact, the content of stored molten salt is in its minimum amount in early hours of the day that the charging time starts, and it causes the abrupt degradation of storage temperature from set point. To cope with this and keep the storage temperature around its maximum point (550˚C), the process control is accomplished by imposing a recycle line based control design, where cold molten salt circulates around the solar field at early hours of the day (charging time) from exit of solar collector field back to the entrance of collector field to heat up at desired temperature. This solution is applied when the amount of hold-up in storage tank is at its minimum, i.e. at the starting hours of the day, and the temperature is sharply decreased. To compensate this, it is necessary to provide the desired temperature of molten salt before storing the storage tank. Thus, the recycle controlling scenario operates until the temperature of collector field outflow reaches to the set point (Figure. 2).

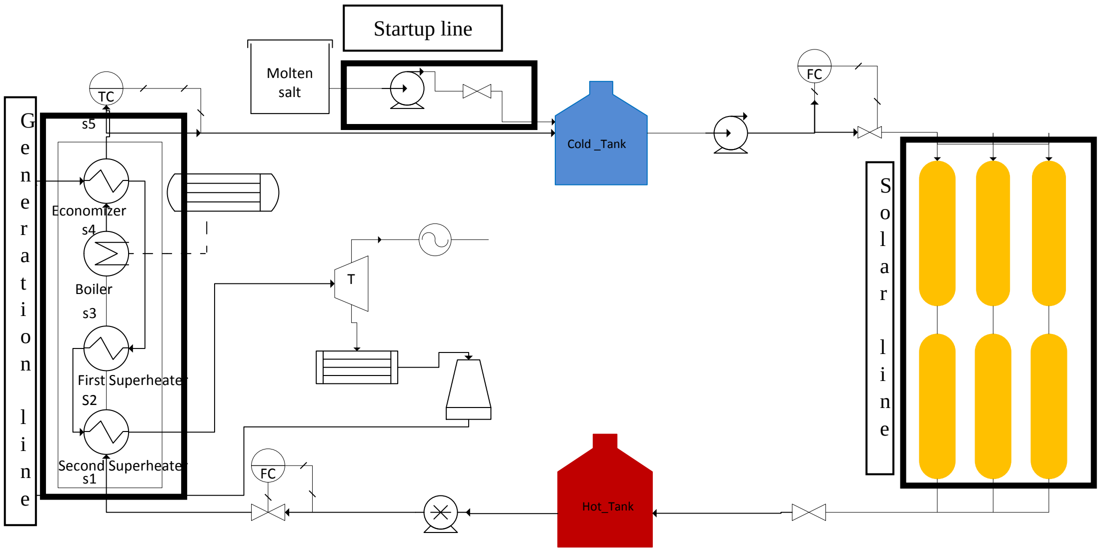


Figure 1.Direct double-tank thermal energy storage technology of CSP plant

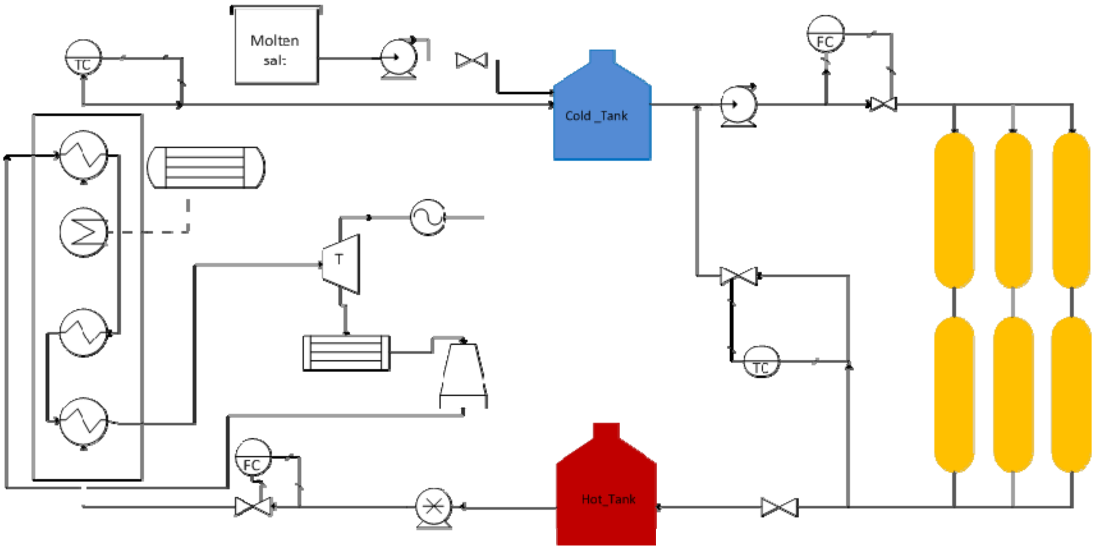


Figure 2.Control based design of double-tank thermal energy storage technology of CSP plant

4.3 Direct Single-Tank Storage

The other common configuration of sensible heat storage based on one storage tank, is single storage tank, which is benefited of thermal stratification in the tank and is called thermocline tank. The main interest to apply the single-tank technology in the design of CSP plant is eliminating the extra volume in storing the cold and hot fluids inside a single tank (Herrmann et al., 2002); as a result, lessening the capital cost, also maintenance and operational cost of the second tank. Although thermocline TES technology from economic point of view is appealing to apply, this approach technically brings the stratified layer challenges in storage tank and complexity in control. Owing to the buoyancy forces, it provides two isothermal regions stratified vertically and separation line is specified by a thin layer as the interface between cold and hot fluid in higher temperature gradient (Yang et al., 2010). Furthermore, energy is added to the thermocline tank via hot fluid entering from the top of the tank and cold fluid discharging from the bottom (half-cycle charge). To recover the stored energy to generate the power, hot fluid leaves the top of the tank in reversed direction flow to compensate (a half-cycle discharge). During energy charging processes, hot fluid is loaded into the tank from the top and at the same time cold fluid at the bottom of tank is pumped out to the solar field to absorb heat from the sun. Because of the density difference between hot and cold fluids contained in the single tank, molten salt naturally stratify in the tank (Li et al., 2011). Therefore, modelling of these physical phenomena by simulation tool to define and separate the hot and cold fluid is particularly complicated. To evaluate the phenomena and its control, different control scenarios are scheduled due to specify the performance of the fluid with temperature differences and separating cold and hot fluid due to lead the hot fluid into the HEX block to proceed the routine process and cold one drawing back into the solar field (charge half-cycle and discharge half-cycle) (Figure.3).

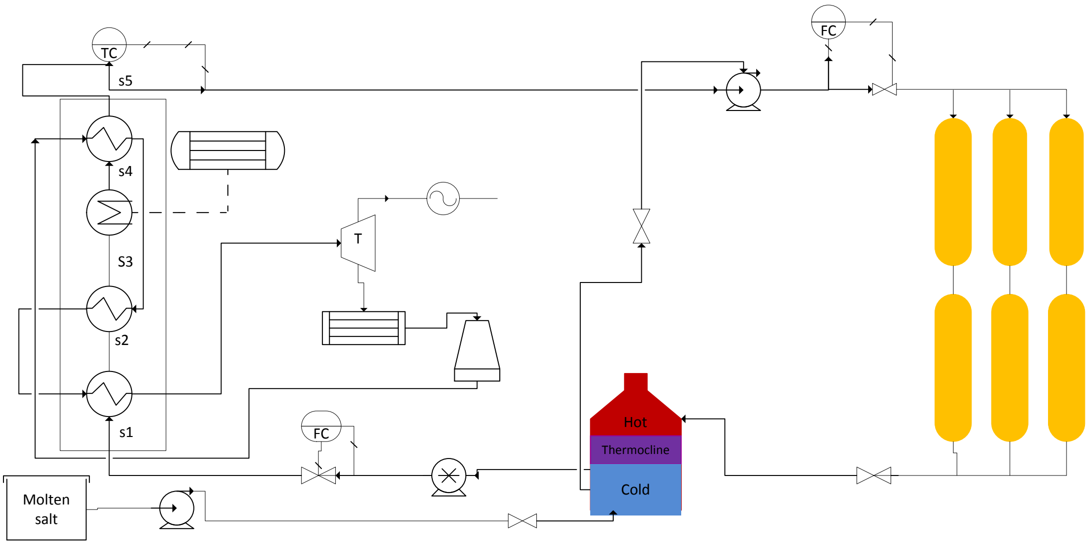
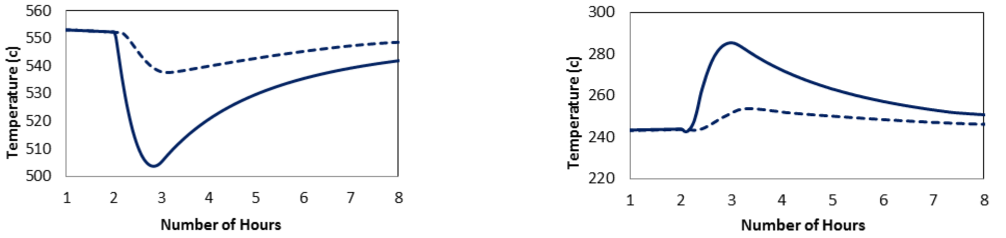


Figure 3. Single-tank thermal energy storage technology of CSP plant

5. Simulation results and discussion

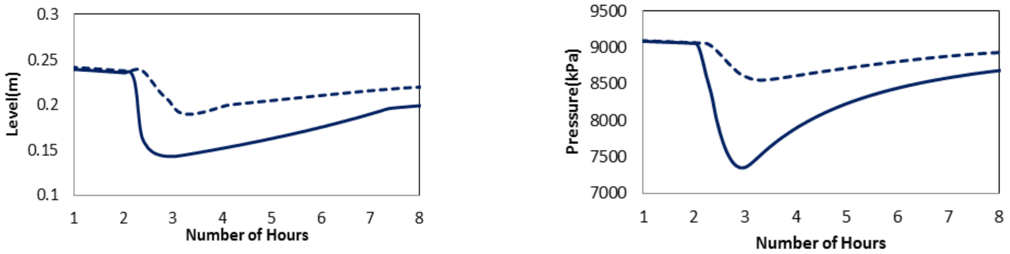
5.1 Direct Double-Tank Storage : Conventional vs. Rational

As it explained earlier, the plant wide issues in controlling the CSP plant elevates the significant efforts about the need to providing the desired temperature of the outlet of collectors. The fact is though plantwide controllers are applied through the process, the problem is derived beyond the common control solutions. Since at night which the radiation is null and the storage is started to discharge, a drop is observed in the overall efficiency of the power plant, despite conventional controlling the stored thermal energy. The matter of the face is that it is impossible to keep storage fluid temperature at its maximum when the storage process is started (Rovira et al., 2011). For more clarification, it is worth stating that the quantity of storage in the hot tank decreases abruptly at the earlier hours of the day (the end of discharging period, which is linked to the next charging period). Thus, at following charging period, a complete cold molten salt (290°C) is pumped into the solar field. Obviously providing the set point temperature for storage (550°C) does not occur straight after daily startup. In this period, the further units of the plant might disturb and some deficiencies take occur in the effectiveness of the entire plant. To cope with this, the common solution is applied as the strategy of recycling the leaving HTF from solar field back into the entrance of collector (Figure. 2). This strategy causes the circulation of HTF into the solar absorber pipes until meeting the set point in the output of collectors, where the HTF flows into the storage. Undeniably, the recycle line draws the process to harvest the energy optimally and is stabilizing the results in dynamic of effective variables. As it can be seen in Figure. 4, the comparison of discussed designs, i.e., with recycle of molten salt into the collector field and without, presents the remarkable improvement in plantwide control via applying the recycle based design control, which it is shown in the variables of the HEX block and power block. To preserve the added loads in these sections, reducing any disturbances or offset from set point, enhances the efficiency of plant. Moreover, the effect of this control scenario represents the stability in the control of the variables in HEX block. It should be noted that the design without recycle line imposes more load to components due to wide range of variations in critical parameters such as pressure in vessel, which consequently would consume more power and thus, more expenses might be suffered from in these blocks. Then, a significant feature of imposing a recycle line in the design of current double -tank TES design is to prevent the extra load on HEX block, which derives the process to save energy instead of consuming more energy.



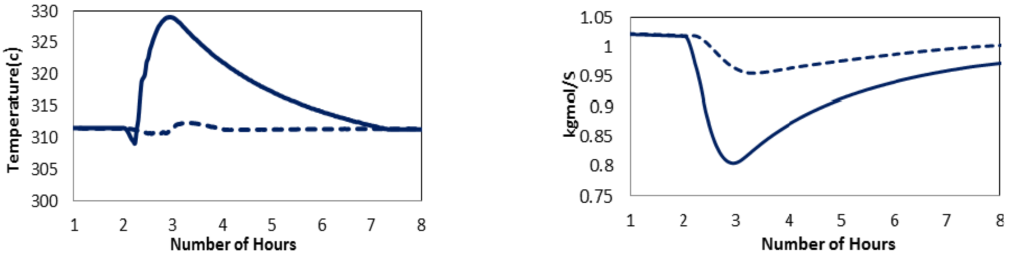
a)Temperature of hot storage tank

b) Temperature of cooled steam in power block



c) Level of water in vessel boiler

d) Pressure of vessel boiler



e)Temperature of vessel boiler

f) steam flow rate in power block

Figure 4. Effect of flow back design in performance of HEX block in double-tank CSP (dashed line: with flow back, bold line: without flow back).

Figure. 4.a shows the less degradation in temperature of storage around set point in the case of lending support to the recycle line, in discussed early hours of the day, though it is shown that in conventional design, the degradation is five-folds than the previous case . Therefore, the resulting effect of control on storage temperature in the outlet of collector confirms highly improvement in preserving the energy load for storage. The analogous comparisons are in common for the further variables of the HEX block as it can bee seen in Figure.4. For instance, the degradation of pressure in vessel boiler (Figure. 4. d) is intensely reduced if the recycle line is modeled. Moreover, in recycle configuration, the level, temperature and pressure loaded into the vessel boiler are controlled nearly around the set point in comparison with the conventional design. However, to avoid extreme degradation in dynamics of variables, it is strongly confirmed that the recycle based design diminishes the deficiency of the performance. Furthermore, for the safety point of view and correspondingly, saving energy to decrease the load on the system, qualifying the performance of tube bundle as a function of the operational conditions is important to consider and improve.

5.2 Direct Double- Tank and Single- Tank Storage

The comparison of the results derived from the dynamic simulation are presented with respect to the level of storage tank in aforementioned TES technologies, through the 24-hour charging and discharging periods in Figure.5. According to the results, it can be seen that the slight rising up of molten salt volume into the cold tank, which is gradually filled up by cold molten returning back after one round cycle through the process. In this period, which is spent since midnight to sunrise, the system is supplied by loaded molten salt from hot tank and the system is served to produce the power. Hence, the level of both tanks follows up the divergent process before sunrise, i.e., one fills, while the other one empties. After sunrise, the trends are inverted since the solar radiation is going to be harvested into storage tank and the cold molten salt might be pumped down in the solar field to be heated. At sunset, the maximum level of TES is achieved. Except sunrise and sunset instants, the level of molten salt varies linearly in the tanks (linear accumulation of thermal energy). Following the Figure. 5, the liquid holdup can be observed within cold and hot storage tanks. Trends confirm the linear behavior of thermal energy storage of molten salt though the CSP plant. The liquid holdup of hot molten salt (thermal energy storage) gradually increases during the day in spite of the liquid holdup of cold molten salt practically. It means that when the solar radiation is harvested, some quantity of molten salt is sent directly to generate steam while some portion of that is collected as thermal energy in the hot tank. Conversely, the hot holdup is consumed during the night since it supplies the steam generation, though the solar radiation is unavailable and solar line is completely off. In CSP plant, storing of energy depends on the quantity of hot molten salt content stored in the hot tank. Thus, the energy stored is a entirely capacitive system and the liquid level is directly corresponded to the available thermal energy storage, which is governed by the total mass conservation principle:

Energy storage=Input- output+ production

Since no reactions occur in the energy storage tanks, for the selected energy storage the conservation principle reduces to:

Energy storage=Input-output

$dM/dt = M^{\cdot}_{in} - M^{\cdot}_{out}$

As the technology is applied as molten salt direct two-tank technology and energy storage is placed on the main process streams which, is fed directly by energy without any utility, process or heat exchanger. It means the input of each tank (cold or hot) is not equal of the output of that. Therefore, the system encounters the accumulation in process. If it is assumed that molten salt is incompressible and is negligible to have a fast transient of filling operation of the molten salt streams, then:

$F^{\cdot}$ (out,hot tank)= $F^{\cdot}$ (in,cold tank)
$F^{\cdot}$ (out,cold tank)= $F^{\cdot}$ (in,hot tank)

Obviously, it is the consequence of balanced behaviors for the liquid holdup between the hot tank and cold tank. Moreover, the volume of storage varies linearly according to the inflow and outflow, Specifically, the level of molten salt in cold tank increases during the night and conversely, of the hot tank rise up in hot tank during the day.

Then, for the night time:

∴ $F^{\cdot}$ (in,cold tank) > 0
∴ $F^{\cdot}$ (out,cold tank)$= 0$

Conversely, the volume of molten salt in hot tank elevates in daytime by:

$F^{\cdot}$ (in,hot tank) $>$ $F^{\cdot}$ (out,hot tank) > 0

It is worth to highlight that the advantageous of this control system appears in controlling the load of HTF in the storage tanks. As it is shown in Figure. 5, the level of HTF in storage does not deplete completely the storage in the end of discharging period. This is considerable from the energy efficiency point of view, safety and maintenance in the process, which keeps the power block at least in its base load and not lead it to complete zero power generation caused by zero volume of the HTF in the hot tank (the least amount of the HTF in the current simulated process is around 1-2 m of the tank height).

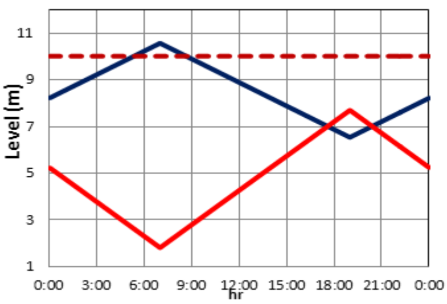


Figure 5. Level of Molten salt dedicated to TES. Solid: double-tank TES (blue: cold tank; red: hot tank). Dashed: single-tank TES.

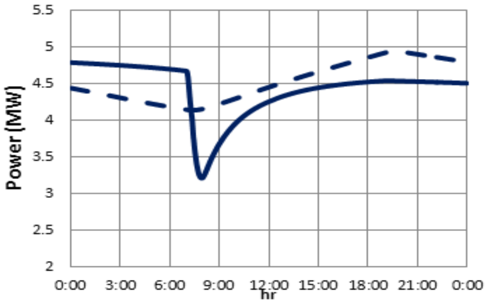
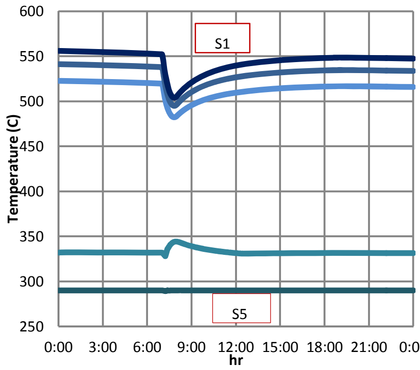


Figure 6. Power generated by CSP plants (solid line: double tank TES; dash line; single tank TES).

On the other hand, molten salt streams in the single tank TES technology continuously circulates over day and night and, therefore, TES does no longer possess the content of hot molten salt stored in the dedicated tank. However, the temperature variation of TES in single-tank technology induces the constant level and more fluctuated trend in power generation around sunrise and sunset (Figure. 6).



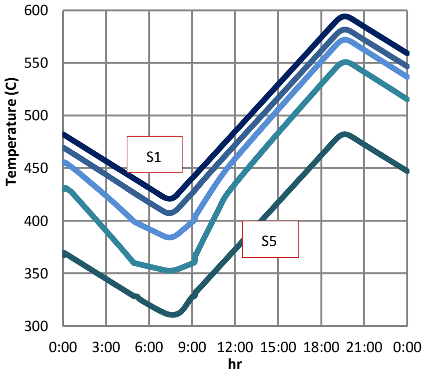


Figure 7. The temperature profile of molten salt stream at the HEX block in double-tank TES.

Figure 8. The temperature profile of molten salt stream at the HEX block in single-tank TES.

Figure. 7 and Figure. 8 show the temperature profiles of molten salt streams at the HEX block. With reference to the Figure. 1 and Figure. 3, streams S1 to S5 are dedicated to the hot molten salt in the inlet of HEX block to the exit stream of block, respectively. For example, S2 would be the exit stream from the second superheater, S3 from the first superheater, S4 from boiler, and S5 from economizer, where is the last unit of the HEX block. The trends of temperature for molten salt represents the decreasing from S1 to S5 monastically (these two captions are shown in the corresponding figures due to not make mess in them). It is clear that the double-tank TES technology offers a more stable temperature changes in the HEX block, giving the possibility of management of the power generation, whereas single-tank TES technology might necessitate a tracking system to regulate the set points of the dedicated control system so as to make more stable the steam production and therefore the sustained power generation. In addition, it can be observed a transient degradation at initiation time of charging in double-tank TES (Figure. 7).This occurs due to mixing of the molten salt entering into storage tank at the beginning of charging time that molten salt inside of storage tank utilized in the discharge time, are not completely in higher temperature (in other words, confluence of the molten salt above 550˚C and molten salt below 500˚C). Conflation of this aspect with the fact that at sunrise the TES is the minimum temperature of that in all over the day, it confirms this point that the holdup contained in the hot tank at sunrise is not sufficient amount to control and smoothen disturbances of the temperature of inlet molten salt stream.

As it is shown in Figure. 8, a completely different behavior is observed as the system does not follow any steady behavior for temperature, inducing certain variations in the steam generation with problematic issues for the control systems. It is worth underlining that the stream S4 in the single-tank TES of Figure. 8 has been appeared in a perturbed trend with respect to the adjacent temperature profiles. It is due to the almost constant temperature of the boiling water within the steam generator that mitigates the temperature dynamics in correspondence with the boiling point of water for the high latent heat necessary for steam production. Conversely, the degradations for the double-tank are already discussed elsewhere (Vitte et al., 2012). As a result, certain stiffness in control and management of the single-tank TES must be considered to provide the optimal design. Obviously, single-tank TES technology is less flexible than double-tank TES technology under special conditions. Indeed, the generation of power at double-tank TES might start the same day of the start-up of process since the quantity of molten salt is promptly close to reach to the desired temperature and then, is partly used and is partially stored. On the other hand, the single-tank TES might need more than one-day charging to meet the anticipated temperature of stored molten salt in the tank.

5.3 Economic considerations

Thermal energy storages is significant to extension of the process of the CSP plant in daily operations and also the reduction of the cost (Li et al.,2011).To have rough cost estimation to compare and improve the possibility of above-mentioned simulated technologies in terms of layout of process, start-up conditions, initial operating conditions, could be taken into account the number of applied main equipment (Figure. 1), which could reduce the capital cost of the plant (Peters et al., 2004). Evidently, double-tank TES technology requires one pump, one control loop and one tank more (although usually smaller) than the single-tank TES technology, making it less appealing for investments. Moreover, single-tank TES technology is shown to have less operational costs with respect to the double-tank TES technology (Li et al., 2011). Nevertheless, the systems need to be compared also from the power generation system stability and flexibility to follow the energy demand, for which the single-tank TES seems to be preferable. Future detailed studies will focus on this point.

6. Conclusions

As it was demonstrated in design of the TES technologies of CSP plants, TES is increasing the operational stability, reducing the intermittence caused by the instable solar radiation through the day and night. A conceptual comparison of different direct thermal energy storage technologies of CSP plants is accomplished based on the dynamic design and storage control scenarios. The work assesses the plantwide control of the conventional designs on CSP plants. The dynamic simulation of each technology provides the opportunity to overcome the issues in control of the process with respect to the operability, flexibility and, controllability through the charging and discharging time (day and night).The control design modification on double-tank storage shows the remarkable effective on the storage quality and stability of power production. In addition, the design of the single-tank technology might be interesting from technical point of view, though it operates under the sever control scenario in comparison with the double-tank technologies due to the complexity in control of the storage and consequently, the operative power generation.

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