CHEMICAL ENGINEERING TRANSACTIONS

VOL. 32, 2013

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at: www.aidic.it/cet

Chief Editors: Sauro Pierucci, Jiří J. Klemeš
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**ISBN** 978-88-95608-23-5; **ISSN** 1974-9791

DOI: 10.3303/CET1332204

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

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The paper presents the numerical and technical comparisons between the direct thermal energy storage (TES) technologies with economic considerations in beneficial design and control to lead the process up to the sustainable power production for the concentrating solar power (CSP) plants. The analysis is performed based on the available data in the previous work on 5 MW Archimede plant operating in Sicily (Vitte et al., 2012). Considerations on process control, operability and design improvement in the layout of plant and flexibility related to the selected TES technologies are provided in this work due to making the decisions for optimal control.

## 1. Introduction

Dynamic simulation due to evaluate and improve the design and control of the solar power plants might compete with special considerations on enhancement of in storage techniques to use in demanded period. In order to provide the stability in production, overall concerns in solar power plant, competition and comparison of common storing technologies should be taken into account to prolong and sustain the delivery of this energy in power block to generate the electricity. With this aim, harvesting of energy by appropriate thermal storage technologies is directly connected to produce the high quality power. Hence, to controlling and troubleshooting of perturbations caused by the intermittent source, the necessity of the flexible design and controllable intermediate facilities might be required to transfer this unstable energy to stable production for peak demand times (Herrmann et al., 2002). This research activity is mainly focused on the dynamic simulation of two different TES technologies adopted typically in concentrating solar power plants to assess the effectiveness, controllability and flexibility in terms of harvesting and conversion.

## 2. Concentrated Solar Power Plants

Solar energy technologies could be categorized in terms of definition and division of applied systems. In general, concentrating solar power (CSP) plants are subdivided into following inclusive 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 procedure from solar energy in PV technology or in terms of 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).

### 2.1 Concentration Technologies in CSP plant

The common technologies through the collection of energy due to focus and transfer into the plant are divided into several classifications, though totally followed the common concept to focus the sunlight onto a receiver, where heats heat transfer fluids (HTF) flowing through the pipelines of concentrators (Pavlovic et al., 2012). The concentration technologies are well-known as: *parabolic troughs*, *power tower*, *parabolic dishes (dish stirling)* and Fresnel *reflectors* (Muller et al., 2004).

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, Chemical Engineering Transactions, 32, 1219-1224 DOI: 10.3303/CET1332204

## 3. Thermal Energy Storage in CSP Plant

Thermal energy storage (TES) system is an intermediate and critical subsystem of solar power plant to store and dispatch the concentrated energy into power block (electricity generation). Although heat integration is typically considered in steady state, the process suffers from vigorous dynamic behavior. Moreover, TES is intrinsically dynamic by definition and therefore, system needs to provide flexibility to collect heat or cooling at one time and deliver it for a later time. Due to meet this, the dynamic simulation is the proper methodology to investigate these systems. As it is well-known, TES concept is structured by transporting the thermal energy with accumulation of HTF into the storage tank (Yang et al., 2010), based on storing heat energy through the day light – as called *charging time* – and afterward, consuming that through the night – as called *discharging time* – which causes the gradual falling the temperature of charged storage down till further sunrise.

Through the process, heat transfer liquid as a circulating fluid through the entire plant flows over the solar collector to heat and rising up its temperature before being pumped into the thermal storage tank to store and produce the steam harnessing to power the electricity generator (Vaivudh et al., 2008). Afterward, the cooled HTF is pumped back into the cold tank or directly to the collector field (based on applied technology single-tank or double-tank storage) and to be heated in another time.

### 3.1 TES Technologies in CSP plant

Thermal energy storage technologies are generally categorized in terms of applied process 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 difference between them is determined according to the location of the thermal storage tank related to the medium and transfer material, heat exchanger (HEX) block, pump, valve and number of practical utilities.

### 3.2 Active and Passive Systems

An active storage system is specified 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 (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 two-tank system (Vaivudh et al., 2008).

## 4. Dynamic Simulation, Control and Design Considerations

### 4.1 Direct double-tank storage Design

The following layout (Figure 1) is the typical double-tank storage applied in solar industrial plants with highlighting on TES due to its flexibility in loading the energy and its performance and sensitivity in heat exchanger block with nominal amount of radiation in 77MW (Archimede plant, Vitte et al., 2012) based on routine sunny day in summer starting from 7-8 AM, afterward, with constant radiation through the day within 10-12 hours, and reducing the radiation rate in 7-8 PM to zero that the stored energy is started to use peak demand hours since sunset till the next sunrise. The produced power would be depended on the performance of process and TES in terms of charging volume. Due to controlling the temperature of HTF flowing into the heat exchanger (HEX) block, flow controller is set to 135 kg/s in the exit of hot tank, where is dimensioned to 10 m diameter and 24 m height, while it flows into the tank from collector filed in 270 kg/s. By definition, charging scenario is initialized by starting the day, rising the temperature up due to charging in the storage system, is set to take occur in one hour by initialization the radiation and controlled simply in outlet of collector. 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 Direct Single-tank Storage

Technically, single-tank TES technology (Figure 2) reduces the storage volume by merging the cold and hot tank into one single- tank and consequently, it eliminates the capital cost of applying the second tank (Herrmann et al., 2002).

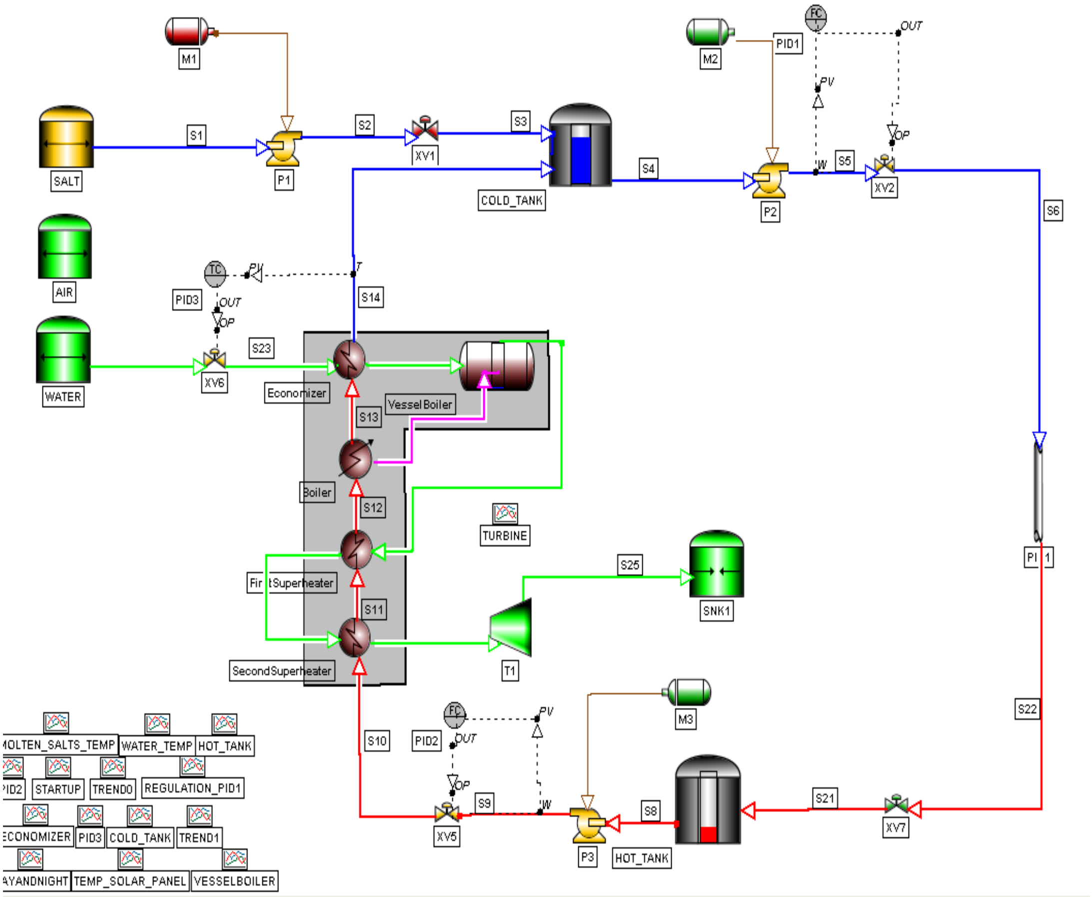

*Figure 1.Direct double-tank thermal energy storage technology in CSP.*

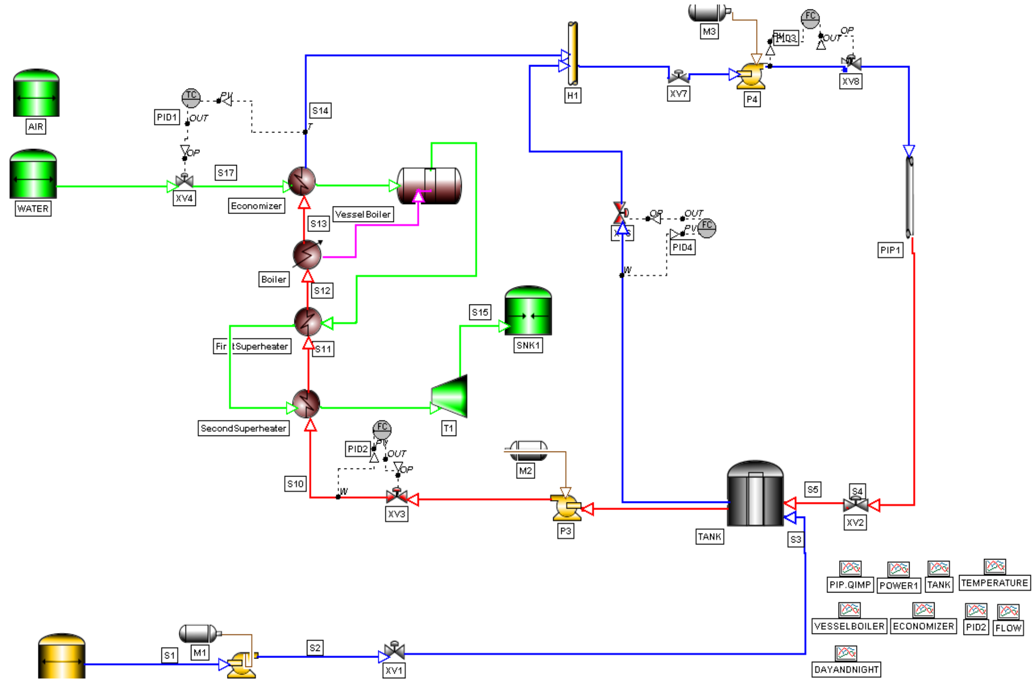

*Figure 2.Direct single-tank thermal energy storage technology in CSP.*

Because of the density difference between hot and cold fluid contained in the single tank, molten salt naturally stratifies in the tank (Li et al., 2011). Therefore, modelling this physical phenomenon by simulation tool to define and separate the hot and cold fluid is particularly complicated to evaluate the actual phenomena and its control. Different control scenarios are scheduled due to specifying the performance of the fluid with temperature differences and separating cold and hot fluid due to lead the hot fluid into the HEX block and proceed the routine process and cold one drawing back into the solar field (charge half-cycle and discharge half-cycle).

## 5. Simulation results and discussion

The comparison of the results derived of dynamic simulation with respect to the level of storage tank is presented in Figure 3. Aforementioned technologies in TES are considered based on charging and discharging volume of tank due to assess the performance of plant through 24 h. The volume of molten salt slightly rises up into the cold tank, where is gradually filled up with cold molten returning back after one round cycle in the process. In this period, i.e. since mid-night to sunrise, the system is supplied with loaded molten salt into the hot tank and the system is served to produce the power. Hence, the profile of level in both tanks follows up the divergent behavior before sunrise, as one tank fills up and the other one empties down. After sunrise, the trends are inverted since the solar radiation is harvested into storage tank and the cold molten salt might be heated until sunset. At sunset, the maximum level of TES is achieved, except sunrise and sunset periods that the level of molten salt varies linearly (linear accumulation of thermal energy) in the tanks (for detailed mathematic models, see Manenti and Ravaghi-Ardebili, 2013).

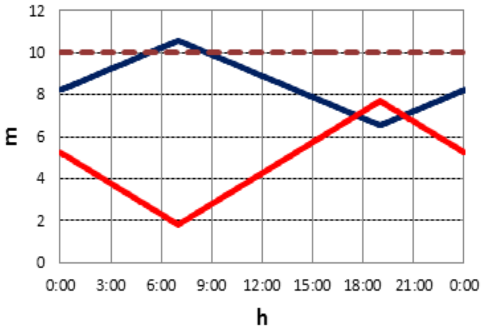

*Figure 3. Molten salt level. Solid: double-tank (blue: cold; red: hot). Dashed: single-tank.*

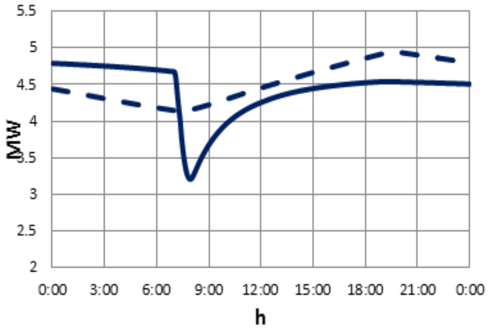

*Figure 4. Power generated (solid line: double tank TES; dash line; single tank TES).*

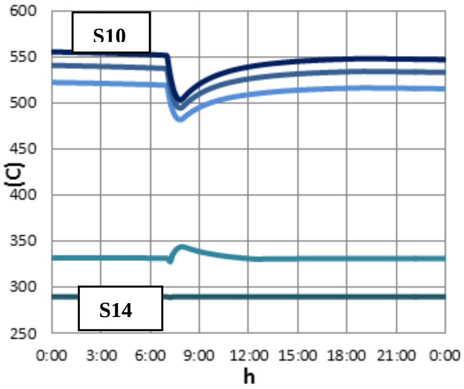

*Figure 5. Molten salt streams within the HEX block in double-tank TES.*

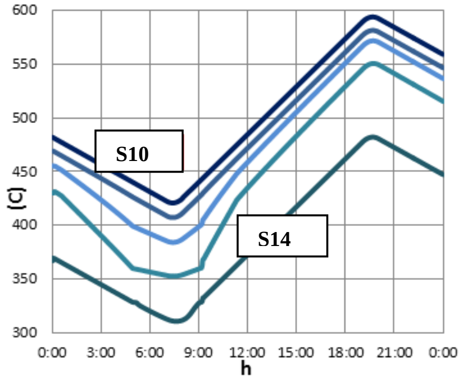

*Figure 6. Molten salt streams within the HEX block in single-tank TES.*

On the other hand, molten salt circulates continuously in single tank over day and night and therefore, TES is no longer the quantity of hot molten salt stored in the dedicated tank for hot salt, but the temperature of the molten salt in the single tank. The temperature variation of TES in the single-tank technology with constant level induces an oscillated trend in power generation around sunrise and sunset (Figure 4).

Conversely, the oscillations 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. For more illustration, it can be stated that single-tank TES technology is less flexible than double-tank TES technology to provide the sustained power under special conditions. Indeed, the generation of electrical power in the double-tank TES might start the same day of the start-up of plant, since the quantity of molten salt is promptly adjacent to achieve the desired temperature and then, is partly used and partially stored. On the other words, the single-tank TES might need more than one-day charging time to cover the set point temperature of stored molten salt in the tank. To demonstrate this fact, Figure 5 and 6 show the temperatures of molten salt streams in HEX block. With reference to the Figure 1 and 2, S10 to S14 are the flowing streams of hot molten salt in the inlet of HEX block to the exit stream of block, respectively. Obviously, S11 would be the exit stream from the second superheater, S12 from the first superheater, S13 from boiler and S14 from economizer, where is the last unit of the HEX block. The trends of temperature for molten salt decrease from S10 to S14 monotonically. It is clear that the double-tank TES technology offers a more stable temperature change in HEX block with the possibility of less stiff management in the power generation, whereas the 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. It can be seen a transient initiation at sunrise in double-tank TES (Figure 5).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 the other words, confluence of the molten salt with 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 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 seen in Figure 6, 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 6 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. To obtain the 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

A first comparison between two direct thermal energy storage (TES) technologies- single-tank storage and double-tank storage - commonly adopted in CSP plants is proposed in this paper by means of two separate dynamic simulations. Single-tank TES appears superior to double-tank TES for control and design, although it appears less flexible from the operational and control viewpoints of steam production and power generation.

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