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Assessment of Direct Thermal Energy Storage Technologies for Concentrating Solar Power Plants

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Dynamic simulation, design improvements and control issues in solar power plants might compete with special considerations on storing techniques along with optimal store technically and from economic point of view. In order to provide the stability in production of power in spite of inconsistency in the source of energy, i.e., sun, overall concerns in the details of solar power plant, competition and comparison of common storing technologies should be taken into account in designation of the plant and plantwide control based on the performance of the storage in charging and discharging periods for the delivery and produce the electricity steadily. This research activity is mainly focused on the simulation of solar power plant for direct thermal energy storage technologies (double-tank and single-tank storage technologies) with DYNSIM™ suite to simulate dynamics and control the entire of plant and FLUENT™ for computational fluid-dynamics studies of thermocline effects in single-tank storage. Assessment of effectiveness, controllability, and flexibility of different direct technologies are brought together with the development of ad hoc control strategies to manage optimally.

1. Introduction

Growing demand to develop and improve upon the sustainable utilization of renewable energies Čuček et al. (2010), the environmental outlooks of energy world (Lam et al., 2011) to follow the clean and free of CO_2 emissions (Lam et al., 2010b), and essentiality of the cost effective energy Klemeš et al. (2010) and in detals by Lam et al. (2010b) induce to consider different design options, intensification (Zhu et al., 2000) revamps, and replacements (Sikos and Klemeš, 2010); to effectively harvest, store, and transform solar into accessible energy (BP; energy outlook, 2012). Any enhancement in the structure, technology and material used in Concentrating Solar Power (CSP) plants to sustain the generation of significant portion of power demand would be considerable Pacheco et al., 2002) and confirmed by (Oro et al., 20120. Consequently, all these inspire the present work dealing with operational assessments of CSP plants for conventional direct Thermal Energy Storage (TES) technologies. As it is common in the CSP plants, the heat transfer liquid (HTF) as the circulating fluid flows through the solar collector to heat and rising its temperature up before pumping into the storage tank and eventually, used for power generation (Vaivudh et al., 2008) or applied as thermochemical process (Ozalp et al., 2009) and also (Piemonte et al., 2010). Afterward, the cooled HTF is piped back to accumulate in the cold tank or directly to recycle into the collector field to be heated, depending on the TES technology applied. Indeed, the concept of TES in CSP plants is structured on transporting of thermal energy by circulation of HTF and accumulation into the storage tank (Yang et al., 2010). In other words, solar energy is used based on loading heat energy through the daylight – charging period – and unloading through the night – discharging period – for constant power generation throughout the day and night. Furthermore, the key role of TES in CSP is dispatching the solar energy for the delayed time due to optimal usage of energy. TES is commonly categorized in terms of functional process and loading method as direct/indirect storage. In direct TES system, HTF acts simultaneously as the storage medium and transferring fluid. However, in indirect TES system, the process would require the secondary medium for storage, which might be selected according

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to the application (Cabeza et.al. 2012). The harvesting of solar energy is directly connected to power generation by TES technologies. Hence, to control and troubleshooting of perturbations caused by the intermittent source, it would be required to comprehend dynamics of TES technologies. The focus is on the direct thermal energy storage technologies that it would be discussed in details in the following sections.

2. Concentrating Solar Power

The common technologies to collect the sunlight and transfer it into the plant are divided into known classifications, whereas all of them follow the same concept. In all of them, sunlight is focused onto a receiver; and heat the HTF up to flow through the pipelines located in the collectors (Pavlovic et al., 2012).In general, TES is an intermediate subsystem in CSP plants to store and dispatch the concentrated energy into the power block. Although the heat integration is characteristically considered in steady state, the system suffers from intense unsteady behaviour. Due to this, dynamic simulation is the reliable methodology to investigate the dynamics of related performances and the effects on the process flexibility. Consequently, it would be favourable to design the control scenario through 24 hours. Assigning the operating aspects might depend on the proper control strategy and TES technology. In addition, HTF is selected based on application, potential of the process to generate power and the range of temperature for demanded storage. In this activity, molten salt is selected (60 % $NaNO_3$ and 40 % KNO_3) due to the high thermal and chemical capacity, stability around 550°C and environmental friendly nature. Therefore, it might be rather beneficial than the other competitive materials such as synthetic oil, which provides temperature of storage around 390°C and it is flammable, as well (Cabeza et al., 2012).

3. Conventional Direct TES Technologies

A more common and applicable technology in direct storage of CSP is double-tank storage (Vitte et al., 2012), where in charging process, the HTF is pumped out from the cold tank into the solar field to be heated up and then, sent to the hot tank for storage in charging process. Conversely, in discharge process, the solar absorber line is completely disabled by the controllers. It is worth to note that HTF is pumped out regularly through the day and night from the hot storage tank to produce power (Li et al., 2012). Schematically the simulated layout of such this configuration is presented in Figure 1. The other configuration in TES technology is function of storing in the single-storage tank. This is also called thermocline tank due to the thermal stratification phenomena in storage tank (Ore et al., 2012). The simulated flowsheet for the single-tank is obeyed the structure as same as the double-tank one, with eliminating extra tank to accumulate the cold HTF and, the consequence equipment such as: pumps, valves and pipelines.

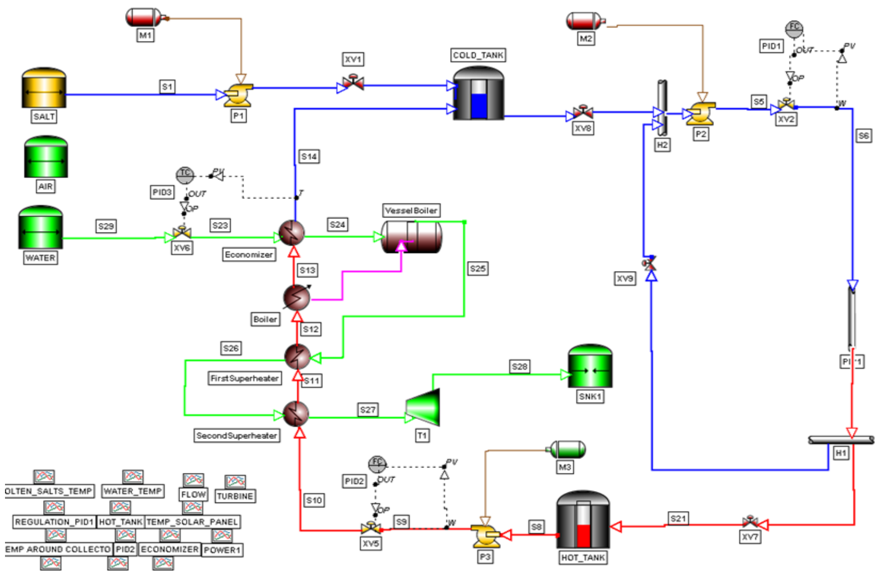


Figure 1: Direct double-tank TES technology

Decreasing the extra volume for storing and related economic issues (the capital cost, maintenance and operational costs associated to the second tank) are the significant motivation of utilizing the single-tank

TES technology in CSP plant (Yang et al., 2010). In this technology, hot fluid is loaded into the tank in charging process, from the top and at simultaneously, cold fluid is pumped out from the bottom into the solar field to absorb heat. Inversely, in discharging process, hot fluid in the tank is pumped out from the top and releases the stored heat to the power plant before returning back to the bottom (half-cycle charge). Furthermore, energy is added to the thermocline tank via hot fluid entering from the top of the tank and cold fluid discharges from the bottom (Li et al., 2012).

4. Operational Assessment

The complexity of the simulation in the solar power plant processes is found when the applied components such as collectors, radiation absorbers, molten storage tank, salt pumps and etc. are not valid in process simulator packages as those in the oil, gas and chemical processes. Thus, some dedicated models or adopted scheme with the available components in would require for reliable simulation (Manenti and Ravaghi-Ardebili, 2013). Unknown nature of thermocline in tank bright the crucial controlling aspects in simulation of CSP plant in thermocline technology. To compensate this defect and also, the accurate controlling design, the plant simulation is linked to the computational fluid-dynamic (CFD) codes. Although, the simulation of CSP plant suffers numerically from the layout complexity and the presence of different equipment, the integration of CFD would lead the design path towards reliable computational efforts. Therefore, the result of CFD modelling has been implemented in dynamic simulation of single-tank technology to predict the behaviour of thermocline and instruct it to effective control scenario.

4.1 Start-up issues

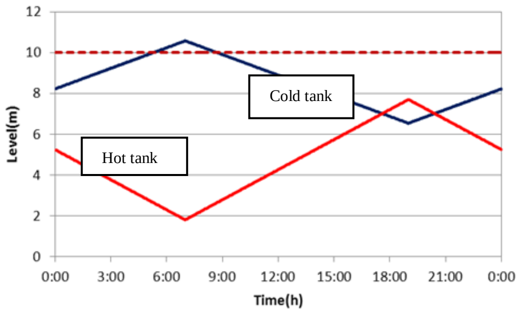
Figure 2.a. represents a trend of liquid holdup in cold and hot tanks (double-tank storage technology) through the charging and discharging period. It evidently represents the linear behaviour of hold up into tanks. During the charging period, the content of hot tank gradually increases and conversely through the discharging period, the harvested energy is consumed and consequently the levels of the stored liquid decreases with a similar slop of the harvesting one. The constant level of the hold up in single-tank storage is simply confirmed by regular loading and unloading the storage tank continually to preserve the same performance inside the tank (see Figure 2.a; dash line). As it is easy to calculate from conservation principle, the stored energy is a function of the input and output of liquid into the tank and the accumulation is governed by the total mass and energy balances:

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out} \tag{1}$$

$$\frac{dH}{dt} = H_{in} - H_{out} + Q_s \tag{2}$$

$$m \cdot c_P \frac{dT}{dt} = m \cdot c_P \cdot \left(T_{in} - T_{out}\right) \tag{3}$$

With analogy to the direct storage in two tanks, storing the energy needs to keep the consistency in the load of tanks. Therefore, the term of accumulation is always nonzero Eq(1). Moreover, storing and consuming the loads in two tanks, are apparently describable with the energy balance Eq(2) that Eq(3) derives with the reasonable assumption when the tank is practically insulated. Though, this concept governs completely the diverse conceptions for single-tank storage, as the process might be managed with one unique tank as storage for loading and unloading. Therefore, the system faces regularly with equal input into the tank and output from the tank. It means that, based on the conservation law Eq(1), the accumulation doesn't occur and system proceeds the regular circulation of the HTF into the tank. This is shown clearly in Figure 2.a as dashed line. To assessment, the efficiency and operability of the two technologies might be considered from the start-up perspective. In this, the system might be pointed out for cold start-up and thermal energy provided for early hours of charging would present the delayed behaviour as it is predictable in the start-up issues of the dynamic processes. For considering these, shown in Figure 2.b, with the identical initial conditions for both technologies, the temperature profile of the cold HTF is not followed by the comparable trends in double-tank and single-tank TES technologies. As it mentioned earlier, according to Figure 2.a, the process with single-tank storage would suffer the lack of accumulation due to the continuity in the loading and unloading Therefore, the prolongation of the system is resulted to obtain the equal temperature followed by double-tank storage process. Then, single-tank TES would need the certain time to achieve the desired temperature (around 540 °C - 550 °C) for accomplishment of proper operations, whereas two-tanks TES technology is rather more flexible since it starts operating as the sun light is available.



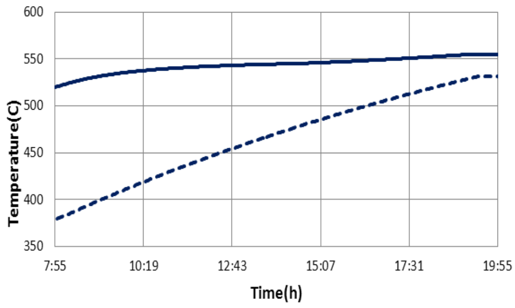


Figure 2.a. Levels of molten salts (dash line: single-tank TES; solid lines: double-tank TES).

Figure 2.b. Temperature trends in cold start-up (dash line: single-tank TES; solid line: double-tank TES).

4.2 Storage tank issues

As discussed earlier, two conventional technologies are well-known for CSP plants based on the number of storage tanks (one or two). Between the mentioned technologies, the single-tank storage is significant to investigate intensely because of the complicated behaviour of stratified fluid in single tank. The stratified phenomenon derives the thermocline region by the differences in the density of hot fluid collected on top of the cold one. Because of the temperature variations in the different levels of tank, temperature profile is needed to be recognized precisely. The important control problem is appeared in discharge period, while it is necessary to control the inlet and outlet temperature in terms of the height of tank. To analyse the temperature evolution in tank through the discharging time (charging time is not discussed for sake of conciseness) and implement it for the optimum control scenario, storage tank is simulated by 3D FLUENT™ suite (Figure. 3). For simulation, the dimension of tank is given 24 and15 m of height and diameter, respectively and, the governed equations of density, viscosity and thermal conductivity for molten salt is assumed by followings (Flueckiger et al., 2011).

$$\rho\ (T)= 1938-0.732\ (T-200) \tag{4}$$

$$\mu\ (T) = \exp\ [-4.343\ (\ln\ (T_1) - 5.011)] \tag{5}$$

$$K\ (T) = -0.000653\ (T-260) + 0.421 \tag{6}$$

As it is shown in Figure 3, the temperature degrades inside the tank as the function of time and depth of tank in discharge time (08:00PM to 07:00AM). Based on the analysis of the CFD result, the separation of the cold and hot fluid at higher temperature occurs in a deeper level of tank, despite the colder HTF separates in upper level. This fact would conduct the process control to figure out the temperature PID controllers and the controlling scenario scheme in DYNSIM as the applied simulator.

4.3 Temperature evolution issues

It is obvious that the temperature of stored molten salt entering into the tank and afterward, passing through the heat exchanger block decreases in heat exchangers to transfer the heat to supplementary water and produce high quality steam. For this purpose, in double-tank technology, because of the ease in the separation of hot and cold fluids in the different tanks and the consistency in the temperature of fluid, there is no remarkable tendency of degradation in temperature, except of some disturbances caused in facing with less quantity hold up in storage tank remained from last discharge, as it seen in Figure 4a. This induces the degradation in the temperature of molten salt around set point while those of the single-tank present significant and wide range degradation due to the thermocline in the tank through the day and night (Figure 4b). Hence, the controlling scenario resulted from these variations in temperature history should be handled with stiff tactics in comparison with double-tank storage that it performs in uniform performance. As it is dedicated for double-tank storage in CSP plant and the analogous situation for single-tank process, the temperature of stored molten salt stated by S10 (see. Figure 1) leaving the storage tank with the peak temperature of storage decreases by exchanging the heat while it passes from the frontward heat exchanger to stream S11 and eventually, to the ultimate stream S14 exiting with 290°C from the economizer (Manenti and Ravaghi-Ardebili, 2013). In this passage, the double-tank storage shows the smooth and flat trends (Figure 4.a); In contrast, the single tank TES reveals dynamic profiles with remarkably different behaviour from double-tank storage (Figure 4.b). Due to the thermocline phenomena demonstrated by CFD simulation discussed earlier in single-tank, it induces a wide range of temperature variations. In comparison with the trends of molten salt temperatures in the single tank by FLUENT (Figure 3), a compromised control scenario with DYNSIM is implemented. Therefore, the control scenario of DYNSIM is reinforced in a more precise way by the result of FLUENT to achieve the optimum design and control of single-tank. The detailed extended results of this work would be presented in the further publication of authors.

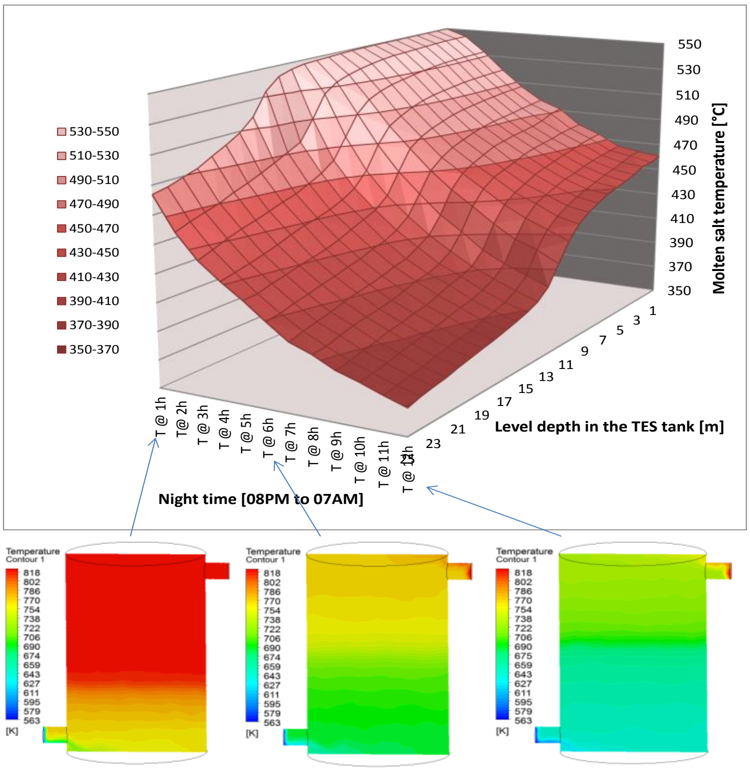


Figure 3: Temperature distribution of thermocline in discharging period (night cycle).

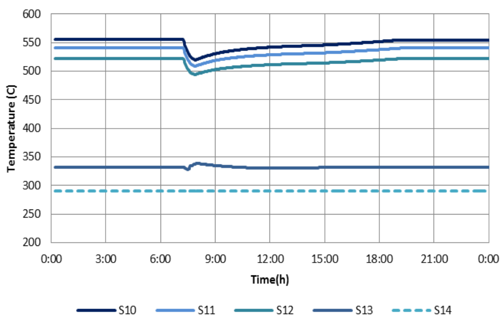


Figure 4a: Temperature profile of molten salt streams: double-tank storage.

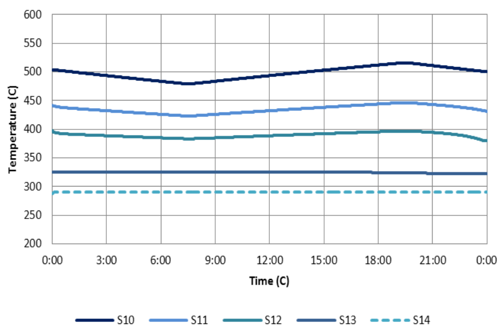


Figure 4b: Temperature profile of molten salt streams: single-tank.

5.Conclusions

This work has proposed the assessment of the performance of different layouts in CSP plant in terms of storage technologies, from the different technical points of view using the dynamic simulation. As it was discussed, double-tank technology might generate power as shortly as the plant is started up. This is possible since the molten salt is directly heated to achieve the desired temperature and, therefore, it can be immediately used for steam generation. Whereas, the process with single-tank needs to spend at least half extra cycle (charging period) to achieve the desired temperature for generating the power similarly. These issues would necessitate well-designed plant wide control schemes due to controlling of the temperature variations. The thermocline phenomena occurred in single-tank storage technology might demand stiff control strategy on the controlling parameters. Two simulators were combined to achieve the results: FLUENT for computational fluid dynamics and DYNSIM for process dynamics. The results of CFD study have been applied directly to handle the control scenario in DYNSIM.

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