Dynamic Simulation of Concentrating Solar Plants

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The discontinuous nature of the solar power forces to study the dynamic behavior of solar plants to characterize their operations, to deepen their process understanding and to improve the performance and maintenance. The present paper described the dynamic simulation of concentrating solar plants with the aim to define a reasonable simplified layout as well as to highlight the main issues to characterize the process dynamics of these systems.

1. Introduction

Solar energy for land applications, but in practice several renewable sources, is characterized by discontinuous nature; on the other hand, although with significant daily, weekly and seasonal dynamics, the energy requirement of industrialized countries can be considered of continuous nature. To meet each other, there is the need to use energy storage technologies (Huang and T-Raissi, 2005, Wilson et al., 2010; Hennings et al., 2011). Energy storage means, for example, to accumulate daytime a certain quantity of energy to be used during the night or, in the case of solar energy, during unfavorable meteorological conditions. Thus, since we are speaking about energy storages and discontinuous nature of power sources, the only way to study the solar energy processes as well as to improve their effectiveness and performances from process system point of view is to pass through the dynamic simulation especially for the systems involving strong dynamics like the concentrating solar plants. Unfortunately, there are not well-established commercial dynamic simulators containing detailed models for such plants, since linear-parabolic solar panels, molten salts, molten salts steam generators, and tanks for energy storages are significantly different from the conventional units adopted elsewhere and traditionally included in the model library for natural gas and oil process simulations (see for example (Manenti, 2012)). There are two possibilities: develop by new the models or transform the existing models so as to make them reasonable for our simulation. If the unavailability of dedicated models will unavoidably lead to their definition by new and, if useful, to their implementation in commercial packages in the next future, this first research activity wants to give an overview of the difficulties behind a dynamic simulation of concentrating solar plants through existing packages. Thus, the key-point is to get a very simplified, but at the same time performing and reasonable, dynamic simulation. Such a simplified simulation is also useful to assess the feasibility and reliability of several very appealing solutions that are going to be installed soon in the solar field such as the real-time performance monitoring of solar panels and units or the optimization of plant transients (i.e. start-up and shutdown) for unit safeguard, plant safety.

2. Archimede solar plant

The Archimede Concentrating Solar Plant (CSP), located in Sicily (Italy), is schematically reported in Figure 1; it consists of two tanks for molten salts storage, series of linear-parabolic solar panels and a steam generator with the associated power generation. The general flowsheet representing the dynamic simulation of the Archimede CSP is reported in Figure 2.

Starting from the tank SALT, the molten salt is entered the plant in the start-up procedure. It is fed to the tank COLD_TANK. An electric motor, a pump P1, and a valve XV1 are positioned on the start-up line. Once the appropriate quantity of salt is entered, the molten salt flows from the tank COLD_TANK to the tank HOT_TANK passing through a pump P2, a valve XV2, regulated by a flowrate controller PID1, and the solar panel, modeled by a pipe model PIP1. The solar energy HS1.Q is provided as external duty to the pipe. This is the typical daytime operation and this process section is called the *solar line*. During the night, the solar line is off, whereas the process section from HOT_TANK to COLD_TANK, called the *generation line*, is always operating at the conditions imposed by the current market demand and power requirements.

In this sense, a dynamic simulation is theoretically able to optimize the power generation and to improve the net margins of CSP by looking at the market demand in real-time and automatically selecting the best setpoints for the power generation. This point will be part of the future developments.

On the generation line, the steam generator exchanges with the hot salts to produce steam from water. The steam generator is really a train constituted by pre-heater, steam generator, and super-heater heat exchanger units. A general and single heat exchanger E4 is intentionally adopted in our simplified layout.

The turbine efficiency is fixed at $\eta = 37.5\%$. The plant is designed to produce 4.7 MW and, according to the efficiency, the vapor flow is estimated in 21.63 kg/s. 135 kg/s of salts have to pass through the heat exchanger, assuming that it is ideally at its maximum performance. This exchanger as an area of 3831 m^2 if its overall heat transfer coefficient is fixed at 0.58 kW/m^2/K. About the heating operation of the molten salts, the receivers are 0.07 m diameter tubes and the total length is about 5400 m (9 strings of 6 collectors each and the length of one collector is about 100 m).The direct solar radiation is approximately 1.9 kW/m^2 in Sicily.

Two tanks for the energetic storage are: 13 m height and 29 m diameter the cold tank; 10 m height and 24 m diameter the hot tank (source: www.enel.it).

Two flow controllers, one for the solar line PID1 and the other one for the generation line PID2, and a temperature controller PID3 for the steam generation (and the check on the minimum temperature of molten salts) are enough to manage the overall system.
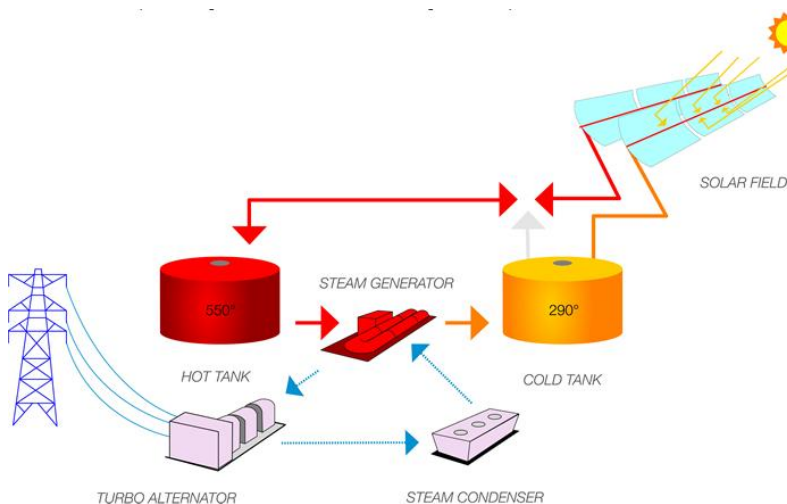

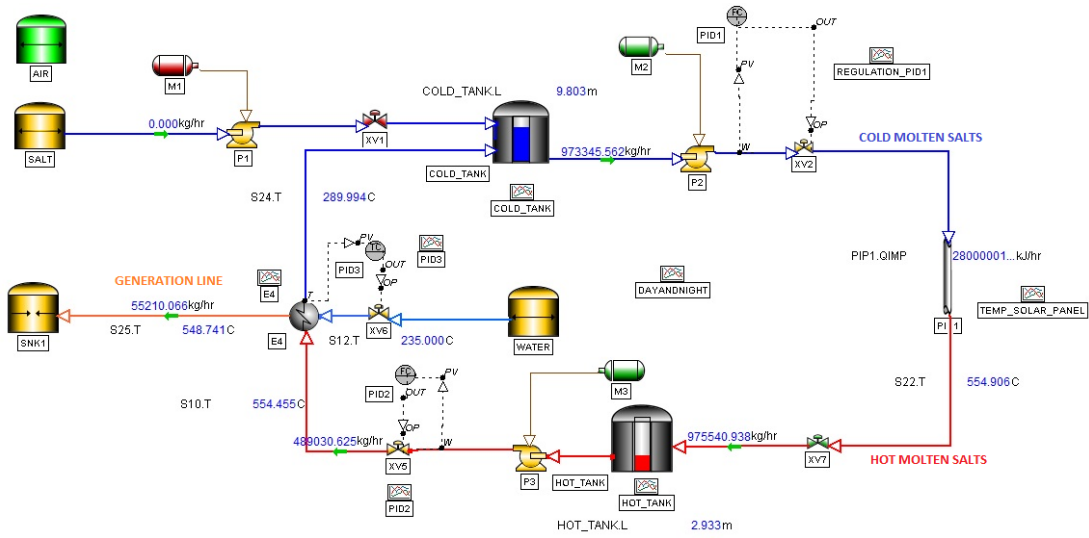Figure 1: Archimede CSP qualitatively layout (source: ENEA, 2012)

Figure 2: dynamic simulation flowsheet (developed in DYNSIM™)

3. Dynamic simulation

Some trends are reported in Figures 3-5. Figure 3 shows the linear trends of molten salts storage tanks, therefore, the energy storage level. Trends are linear since the storage tanks are governed by the overall mass balance:

$$A \frac{dh}{dt} = F_{in} - F_{out} \tag{1}$$

and, being A constant for the cylindrical shape, the COLD_TANK linearly increases/decreases its volume according to the inflow and outflow. During the night it increases the level of molten salts since:

$$F_{in}^{cold} > 0 \tag{2}$$

While:

$$F_{out}^{cold} = 0 \tag{3}$$

Conversely, the HOT_TANK volume increases daytime, when:

$$F_{in}^{hot} > F_{out}^{hot} > 0 \tag{4}$$

Figure 4 shows the dynamics of the molten salt temperature of the generation line after the heat exchanger during the start-up procedure. The start-up procedure is identified by the open command of the valve XV6 (see Figure 2), also plotted in the same figure. The valve starts completely close and, after a certain transient, it achieves the steady-state condition, according to the power generation requirements. The valve dynamics can be optimized and oscillations removed. The temperature of molten salt stream starts at ambient conditions to achieve 290 °C. The temperature is only apparently smaller than the melting point of the salts, since the generation line is originally filled up by inert gas, nitrogen, at 25 °C and 1 bar. While the molten salt enters the stream filling up the pipe and pushing outside the nitrogen, the temperature achieves physically good values. In this case, it is worth underlining that a detailed model is the only way to foresee and, thus, prevent several start-up issues

related to physical inconsistencies of dynamic simulations. At last, the Figure 5 shows the trends of the main temperature of the generation line during the start-up procedure.
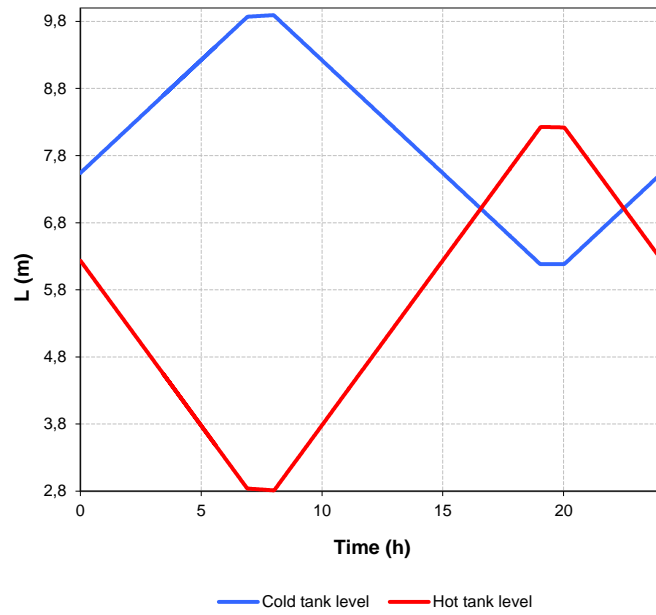

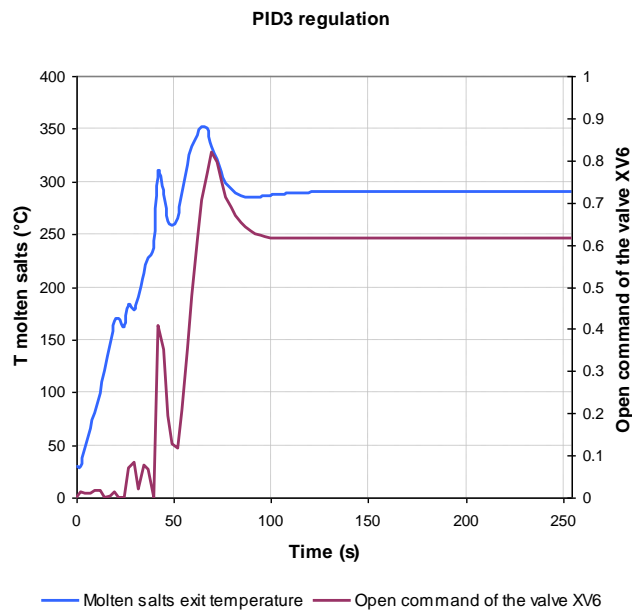*Figure 3: dynamic behavior of storage tanks (24 h-simulation)*

PID3 regulation

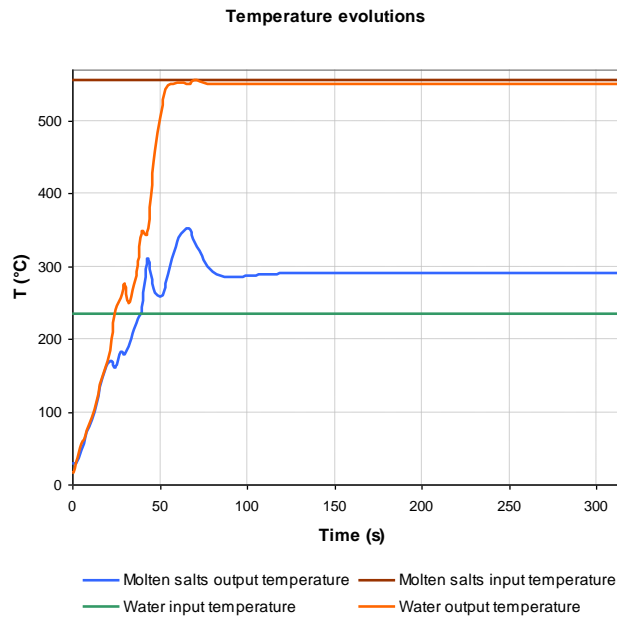*Figure 4: start-up of the generation line*

Temperature evolutions

Figure 5: temperature evolution during the start-up procedure

4. Discussion

The CSP is a promising technology, but it still has certain open operational issues that can make it less appealing than other rival technologies. Some key-issues for the CSP are the following ones:

- The need to keep the salt molten. It means that very fast transients may occur on the solar line and all the operation units on this line may have shorter life cycles for strong dynamics and frequent changes of operating conditions.
- The need to get the maximum economic benefit from the power generation. This is what is required to solar plants to have faster payback and to bridge the gap with other more energetically efficient renewable technologies. To do so, there is the need to optimize the hot molten salt flowrate supplied to the steam generation looking at the peaks of the local/national electric demand (related to hourly forecasting) and provide the surplus of energy in correspondence with the peaks.

Tackling these key-issues means to significantly improve the performances of CSP technology and its net present value as well as to prolong the life cycle of CSP units.

The dynamic simulation plays a relevant role in solving these problems since it allows to assess a priori the effectiveness of controls and procedures to manage the very fast transients on the solar line or to estimate in advance the future performance of the units involved in CSP according to their age and operating conditions. Nevertheless, higher the accuracy that we want on the assessments and previsions, deeper the level of details that we need in the dynamical model for simulating the CSP. Although simplified, the dynamic simulation presented in this paper is a good tool to define certain guidelines and to identify the critical points for simulating CSP dynamics. For example, there is the need to optimize the start-up (but also the shutdown) procedure to save energy and safeguard to units. Moreover, there is the need to activate the solar panels only when the receiver is filled by molten salts to prevent degradation problems or heterogeneous temperatures within the same receivers.

5. Conclusions

The dynamic simulation is a key-tool to improve the performances and the life-cycle of the concentrating solar plants. A simplified dynamic simulation is useful to preliminary check the control systems and procedures to perform the start-up and shutdown operations to save the panels and receivers and the process units as well, but also to identify to main critical aspects in operating the plant. A more detailed dynamic simulation could allow to optimize not only the process transients, but also the net income of the plant by foreseeing the energy demand and, accordingly, storing the energy in advance and generating the maximum power when required. Detailed simulation means the introduction of dedicated models for the heat exchanger (molten salts – water), solar panel, and molten salt storages.

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