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Simulation and assessment of operation strategies for solar thermal power plants with a thermocline storage tank

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Abstract

Thermocline storage tanks are considered one of the most promising options to reduce levelized electricity costs in solar thermal power plants with a storage system. Due to thermocline degradation, the annual electricity yield of a plant with thermocline storage is always lower than the same plant with a two-tank storage system. In this way, an annual performance analysis has been carried out for different charge and discharge operation strategies in order to find out the best operation mode that minimizes the difference in annual yield between both systems. 50 MW_e plants based on parabolic trough technology have been analyzed and both synthetic oil and molten salts have been used as heat transfer fluids. The simulation model has been developed with the TRNSYS© software tool and the advantages and disadvantages of specific operation strategies for both kinds of storage systems have been identified. As a result, differences in fossil fuel consumption, annual yield and startup time for power block have been obtained together with some required changes in hydraulic circuit configuration. The main advantage of these results is that they can provide a useful guideline for further economic assessment associated to thermocline storage systems.

Keywords: Thermocline storage tank; Molten salts; Parabolic trough; Annual simulation

1. Introduction and objectives

Concentrating solar power (CSP) has been shyly commercialized as a renewable energy generation technology but its implementation is expected to grow in the near future. In solar thermal power plants (STPPs), solar radiation is concentrated with the help of mirrors and converted to heat, which drives a power cycle connected to an electrical power generator. An important advantage of STPPs is the possibility of being coupled to thermal energy storage (TES) systems, which allows energy dispatching to meet the required electricity demand.

Parabolic trough systems are the most developed CSP technology, which has generated reliable electricity for three decades. These systems use a field of linear parabolic collectors to redirect and concentrate sunlight onto a receiver tube located at the focal line of the mirrors. Each collector tracks the sun by rotation around a horizontal axis. The heat transfer fluid (HTF) circulating inside receiver tubes is typically a synthetic oil mixture, but some other fluids, such as molten salts, are nowadays being studied.

The two-tank system with molten salts has been the TES option most widely implemented in commercial STPPs, particularly in parabolic trough plants (Relloso and Delgado, 2009). However, the cost of two-tank storage

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systems is still very high, around 30–50 US\$/kW h_t (IRENA, 2012). The cost of storage in STPPs could be reduced with the use of innovative TES technologies such as latent heat storage (Nithyanandam and Pitchumani, 2014) or single-tank thermocline storage systems with solid filler materials. According to the Electric Power Research Institute (EPRI), a cost reduction of around 33% could be achieved with thermocline TES systems (Libby, 2010; Libby et al., 2010).

Up to the present, several studies have analyzed the performance of thermocline storage systems integrated in STTPs, either parabolic trough plants (Kolb, 2011) or solar power towers (Flueckiger et al., 2014). However, the implementation of this type of TES still presents several uncertainties. One of them is the efficiency loss due to the thermocline degradation with successive charges and discharges of the storage (Bayón and Rojas, 2013a), which leads to a reduction in annual yield compared to a two-tank system. In addition, challenges regarding its operation and control still remain unsolved. A proper operation strategy could lead to cost-effective thermocline storage systems in terms of, not only capital cost, but also electricity yield and/or fossil fuel consumption.

The assessment of these uncertainties can be achieved by means of both thermocline tank and STPP modeling. A thermocline tank model integrated in a complete solar thermal power plant can be used to both define and analyze optimized control strategies and study specific aspects of thermocline storage behavior. These are the objectives of this paper, in which the simulation results of the annual performance of such a solar plant are presented, including several model innovations and treatments.

Regarding the thermocline tank model, variation of outlet tank temperature with time is given by an analytical function as proposed by Bayón and Rojas (2014), which in principle reduces the computing time in comparison with other previous numerical models developed for thermocline storage tanks (Kolb, 2011; Kolb and Hassani, 2006; Flueckiger et al., 2013). The solar field model takes into account thermal inertia for simulating transient conditions and incorporates control mechanisms, such as a focusing factor, for dealing with energy dumping and outlet temperature regulation. The simulation of the power block has been implemented by means of an empirical model that considers the operation at a temperature lower than nominal and includes a method to apply a variable startup time.

Different operation possibilities associated to a thermocline storage system have been considered in the present STPP model. In previous studies (Kolb, 2011; Libby, 2010) the electricity yield of STPPs with a thermocline storage tank was simulated and compared with a plant with a two-tank storage system, assuming the same operation strategy for both types of storage systems. Although works such as the one by Wittmann et al. (2011) have dealt with the optimization of operation strategies of STPPs with thermal energy storage, specific strategies that take advantage of systems based on thermocline tanks have not been defined or evaluated till this paper.

Since molten salts have recently been analyzed and tested in parabolic trough plants as alternative to the conventional synthetic oil (Müller-Elvers et al., 2012), their use as HTF will also be considered. In summary, this paper compares the annual performance results of parabolic trough plants with a thermocline storage system under specific operation strategies, using either synthetic oil or molten salts as HTF, with the results of the same plants with a two-tank storage system.

2. Specifications and modeling of STPPs with either two-tank or thermocline storage systems with synthetic oil or molten salts as HTF

Accounting for two different HTFs (synthetic oil and molten salts) and two kinds of storage systems (two-tank and thermocline tank), four 50 MW_e parabolic trough plant types have been considered for the analysis. In all plant configurations the storage material is molten salts and, for the case of thermocline tanks, a solid filler material is also considered. This solid filler is similar to the one tested in Sandia Labs (Pacheco et al., 2002), i.e., consists of a packed bed of quartzite rock and sand leading to 22% porosity. Thus, two different STPP schemes are considered depending on whether the storage fluid is the same as the solar field HTF (direct storage) or not (indirect storage, in which case a heat exchanger is required).

Fig. 1 shows the basic diagrams (a–d) of the plant configurations to be modeled, which include solar field, storage system and power block. The main parameters of these plant configurations are summarized in Table 1. As seen in this Table, the use of molten salts as HTF allows a higher outlet temperature in the solar field, which leads to higher power block efficiency (42% vs. 38% for synthetic oil). This implies that for a 50 MW_e plant with 7.5 h of storage, the thermal capacity of the storage system is decreased from 1000 MW h_t to 900 MW h_t. In addition, having a higher temperature difference in the storage system reduces the molten salts inventory. Moreover, when a two-tank system is substituted by a thermocline storage system with a solid filler material, the amount of molten salt is further reduced.

An important difference between the operation of a parabolic trough plant with synthetic oil as HTF and the same plant with molten salts is the fluid recirculation during nighttime. For the case of synthetic oil, we have considered that the fluid remains in the solar field with no circulation. Hence, when there is no solar radiation, the HTF only recirculates for anti-freeze protection if temperature drops below the minimum value indicated in Table 1 (120 °C). For the case of molten salts, the risk of salt freezing in the receiver tubes due to the high melting point of the solar salt mixture (220–240 °C) (Kearney et al., 2003), implies that solar field temperature should not drop below 265 °C (see Table 1). In order to reduce