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Effect of operating parameters on thermal performance of molten salt packed-bed thermocline thermal energy storage system for concentrating solar power plants

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ABSTRACT

The sensible heat storage in low-cost secondary fillers using a single tank thermocline system offers a cost-effective storage option for concentrating solar power (CSP) plants. A comprehensive numerical simulation of 125 MWh_t thermocline tank is performed by adopting a transient, two-dimensional, two-phase model to investigate the thermal performance of packed-bed thermocline thermal energy storage (PBTC-TES) system. The effect of relevant design and operating parameters on the performance of TES system are examined by analysing the thermocline expansion and local variation of salt and filler temperature. It is observed that the operating temperature difference (ΔT) has ample role on thermal performance of TES system as the efficiency is found to reduce by 12% with increase in ΔT from 50 K to 150 K. Discharging efficiency is estimated to be high at low operating temperature ranges and tend to decrease with increase in ΔT. Also with increase in power output, discharging efficiency tends to reduce slightly since it demands higher flow rates and operating temperature range. In case of inlet salt velocity, discharging efficiency drops by 3.5% when velocity is increased thrice the initial value. Further, a comparative study is performed to figure out the most dominant efficiency determining operating parameter. It is observed that relative to inlet salt velocity, operating temperature range seems to have more influence on the thermal performance of TES system. When the operating range is increased from 50 to 150 K, efficiency drops by about 10% whereas a reduction of only 2.5% is observed when power output is increased from 15 to 35 MW_t for similar ΔT values. Hence, operating temperature range is identified as the dominant efficiency determining parameter of PBTC-TES system.

1. Introduction

The non-polluting, clean, global abundance and inexhaustible features have made engineers and scientists to do an extensive research on solar energy. CSP technology has been widely used for decades to harvest energy from the sun and is used to generate electricity on a large-scale [1,2]. Still, the extended use of solar technologies is limited to the natural diurnal variation in insolation. TES represents the most promising near-term option to achieve self-reliability by allowing it to generate electricity on demand independent of solar collection and it also hinders conversion losses associated with other forms of energy storage. Furthermore, it compensates the intermittency and mismatch between the demand and supply thereby increasing plant capacity factor [3]. However, it is one of the less developed area and only a few CSP plants in the world have tested high temperature TES systems (between 393 K and 873 K) [1]. Different heat transfer fluids (HTF) namely air, synthetic oils, saturated water, molten salt and other gases have been proposed and implemented [1,4–6]. Among these, molten salts are having much lower vapor pressure and are relatively cheaper compared to currently used synthetic oils and also allows for higher storage operating temperatures [7]. Kearney et al. [8] evaluated the feasibility of direct storage system configuration (ie., using molten salt both as HTF in the solar field and storage media in the storage tank) to reduce the levelized electricity cost. Two-tank and single tank stratified storage tank designs are the two different technologies that have been implemented in high-temperature large-scale solar electricity generation plants [9]. The indirect two-tank system was considered to be the most reliable and safe system for parabolic trough plant thermal storage [10].

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However, the cost of this type of storage system adds almost to 20–30% of the total installation cost of the plant [6]. An affordable storage technology is thus indispensible element for a successful operation and economical acceptance of CSP plants. Significant cost savings can be achieved by adopting thermocline storage concept. A single-tank thermocline test bed with dual-media storage, providing up to 5 MWh_t storage capacity has been successfully tested at the Plataforma Solar de Almería [11].

Further reduction of the cost can be achieved by filling tank with low-cost solid fillers which could replace the costly HTF without causing much reduction in storage efficiency [12]. The authors suggested that single tank molten-salt PBTC system is a viable cost-effective storage option in a parabolic trough plant and it costs only about 66% of commercial two-tank molten salt system. This potential resulted in an increased interest in evaluating such systems through modelling and simulations. The schematic of a direct PBTC-TES system integrated with CSP plant is shown in Fig. 1. Pacheco et al. [12] demonstrated an indirect pilot-scale molten salt thermocline tank with 2.3 MWh_t storage capacity and compared the results with two-tank molten salt system. The test results showed that a molten salt PBTC system is a feasible and cost-effective option for thermal storage in a parabolic trough plant. In 2010, Flueckiger et al. [13] formulated a numerical model of PBTC tank with composite walls in which the authors studied causes responsible for the occurrence of thermal ratcheting. Subsequently, a novel tank design to impede thermal ratcheting was proposed and demonstrated by Zanganeh et al. [14], developing a pilot-scale thermal storage unit immersed in the ground to generate thermoclines. Most recently, a laboratory-scale experiment with 8.3 kWh_t capacity was built by Hoffmann et al. [15] where rapeseed oil and quartzite were used as HTF and filler respectively. Authors developed numerical models to predict experimental results over a range of tank scales. However, several technical problems hinder the large-scale utilization of the PBTC system and it is imperative to have an extensive knowledge about the design and operation aspects of the system to overcome these hindrances through numerical modelling [16].

Various numerical investigations and comparative analyses were carried out on the thermal and mechanical aspects of high temperature PBTC-TES system to minimize the extravagant and time-consuming experimental investigations [13,17–24]. The relevant works carried out in this area are based on the model with several assumptions such as constant thermo-physical properties, local thermal equilibrium between the HTF and the filler bed or adiabatic conditions of tank wall which make these models overly simplified. A simplified one-dimensional model was presented by Modi et al. [17] to evaluate system performance based on storage temperature difference and the cut-off temperature difference, and their effects on the cycle duration. The study assumed the effect of thermal conductivity of the filler bed as negligible. However, it does significantly influence thermal diffusion in the HTF region and the overall performance of the TES system [18]. Van Lew et al. [19] developed a one-dimensional numerical model which is solved using method of characteristics carrying only minimal computing time and high accuracy. A generalized chart was then developed which could serve as a tool for PBTC-TES system design and calibration in energy industry [20]. Yang and Garimella [21] presented a detailed two-temperature two-dimensional model to study the discharging process of the thermocline system with molten salt and filler material. The thermal behaviour including temperature profiles and discharging efficiency were specifically investigated and also proposed a guideline for the design of PBTC-TES system.

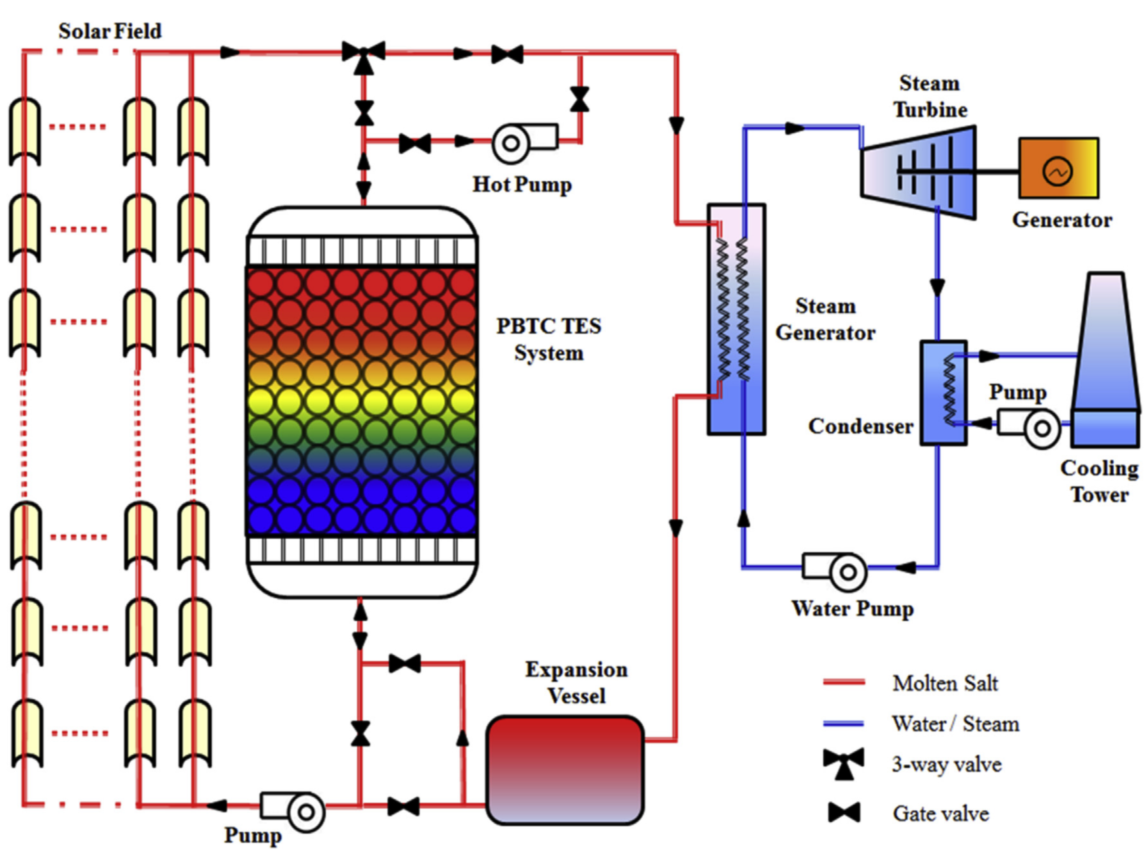

Fig. 1. Direct packed-bed thermocline TES system integrated with CSP plant.