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Research Paper

A novel hybrid storage system integrating a packed-bed thermocline tank and a two-tank storage system for concentrating solar power (CSP) plants

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HIGHLIGHTS

- A novel hybrid storage system for CSP systems is proposed.
- The transient thermal performance of the hybrid system under different weathers is numerically investigated.
- The hybrid system enables the plant to continuously generate power under unfavorable weathers.
- Frequent charge–discharge of the thermocline tank is avoided in the hybrid system.

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ABSTRACT

To overcome the inherent shortcomings of the thermocline storage system, a novel hybrid storage system which integrates a big packed-bed thermocline tank and a small two-tank storage system for concentrating solar power (CSP) plants is proposed. Detailed descriptions of the hybrid storage system are presented and four typical operational modes are proposed. A numerical model is developed for the hybrid storage system incorporated in a hypothetical 50 MWe molten-salt solar tower power plant, and the transient thermal performance under different weather conditions is investigated. The results show that the small hot tank has the buffering effect during short-term solar fluctuations, and thus frequent charging–discharging operations of the packed-bed thermocline tank in the hybrid system are avoided which alleviates the thermocline degradation encountered in conventional thermocline storage systems. The overall heat utilization efficiency of the hybrid storage system can also be improved by utilization of waste heat from the in-depth heat discharging process of the thermocline tank. With the proposed hybrid storage system, the CSP plant can be flexibly run to continuously generate constant power even under very unfavorable weathers.

1. Introduction

In recent years the study of concentrating solar power (CSP) technologies has increased markedly. Thermal energy storage (TES) systems which store solar thermal energy to be used later in unfavorable weather or at night are vital for the CSP technologies, because CSP systems with TES can not only generate stable and dispatchable electricity, but also enable higher overall penetrations of solar photovoltaic (PV) and wind power [1]. Presently, molten salt is the main storage medium used in utility-scale TES systems for CSP technologies, as it can offer the best balance of capacity, cost, efficiency and usability at high temperatures. Molten-salt TES systems can be generally classified into two-tank system and one-tank thermocline system. The two-tank molten-salt TES system which has two storage tanks storing molten salt with different temperatures as illustrated in Fig. 1a is the most developed utility-scale TES system for CSP plants, and has been applied or projected in many CSP plants including the Crescent Dunes tower plant (110 MWe) in USA and the Gemasolar tower plant (19.9 MWe) in Spain. However, the two-tank system has a relatively high cost and limited room for cost reduction, and thus developments of alternative cost-effective TES systems are in urgent need [2–4].

The one-tank thermocline TES system has only one storage tank which can store both the hot and cold molten salt at the same time, as illustrated in Fig. 1b. On the tank there are usually one top port and one bottom port for the flow of hot and cold molten salt,

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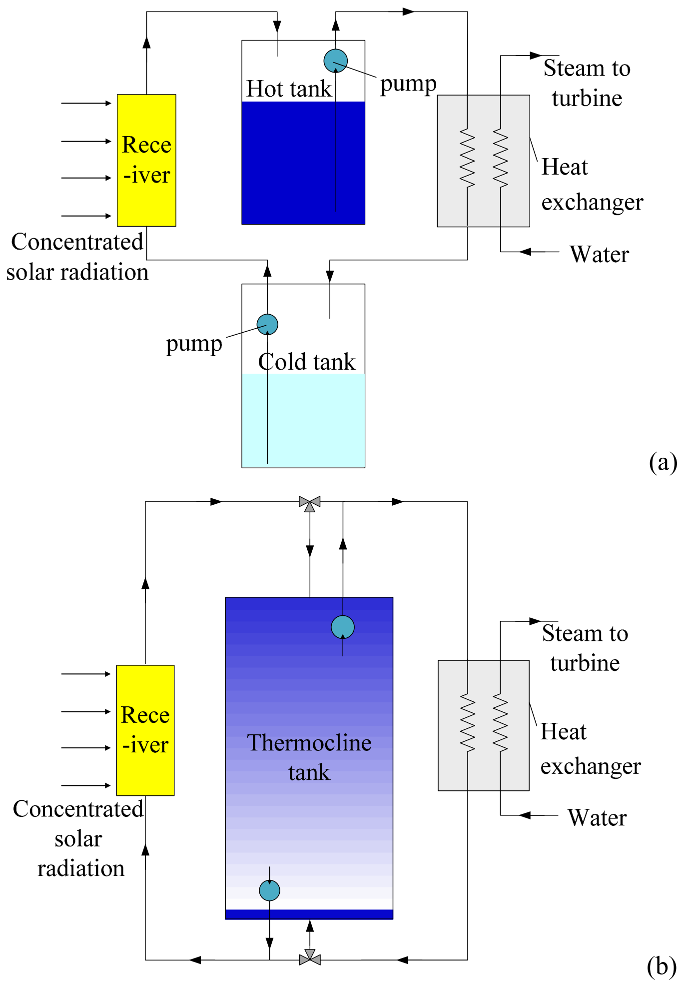

Fig. 1. Schematics of the conventional two-tank storage system (a) and one-tank thermocline storage system (b).

respectively. The hot molten salt and cold molten salt are located on the upper region and the lower region, respectively, and a temperature gradient region, usually termed as thermocline, exists between the hot and cold molten salt. During the charging process, hot molten salt from the solar receiver (for direct storage system) or heat exchangers (for indirect storage system) flows into the tank through the top port, and the thermocline region moves downward. While during the discharging process, the molten salt flows reversely with the thermocline region moving upward. Since the one-tank thermocline system only has one storage tank and low-cost solid fillers can be packed in the tank to replace part of the molten salt (referred to packed-bed thermocline system hereafter), it provides a more cost-effective option for TES systems with a potential cost reduction of 20%–37% [5].

Due to the benefit of low cost, the packed-bed thermocline system has attracted worldwide attention in the past decade. The first pilot-scale (2.3 MWth) packed-bed molten-salt thermocline tank was successfully established in Sandia National Laboratories [6], and quartzite rock combined with silica sand were screened out as the most practical cheap solid fillers [7]. A lab-scale packed-bed thermocline tank was also built by Valmiki et al. [8], and heat transfer behaviors during the charging and discharging processes were experimentally investigated. Bruch et al. [9] experimentally tested a pilot scale oil/rock thermocline TES system. A mixture of silica rock and silica sand was used as the solid fillers and thermal oil was the heat transfer fluid. The flow uniformity and behaviors of multiple charge/discharge cycles were investigated.

Besides the experimental research work, increasing numerical investigations about the packed-bed thermocline TES system have been reported recently. Yang et al. [10,11] developed a two-temperature model for the molten-salt packed-bed thermocline system and carried out a series of numerical investigations. Li et al. [12] developed a one-dimensional thermal model using the modified Schumann equations and numerically investigated various scenarios of thermal energy charging and discharging processes for the packed-bed thermocline tank. Flueckiger et al. [13] carried out a comprehensive simulation of thermocline tank operation, and incorporated it into a system-level model of a 100 MWe power tower plant to investigate the storage performance during long-term operation. Xu et al. [2,3] presented a comprehensive transient two-dimensional two-phase model to investigate the characteristics of the discharging process of the packed-bed thermocline system. The heat transfer characteristics within spherical solid fillers for the discharging process were also investigated based on a modified transient two-dimensional dispersion-concentric (D-C) model [14]. Cocco and Serra [15] numerically analyzed the performance of a 1 MWe CSP plant using the two-tank or thermocline TES systems. The study shows that the two-tank storage system yields a slightly higher performance than the thermocline system, but the thermocline system leads to a reduction of the energy production cost of the CSP plant. Most recently, Wang et al. [16] numerically analyzed the influence of the flow distributions at the inlet and outlet of a packed-bed molten-salt thermocline tank on the thermal performance. The results show that even with a large flow blockage at the inlet, the flow distribution has only a limited influence on the useable energy output. The numerical study of the thermocline storage systems was recently reviewed by Flueckiger et al. [17]

Although the packed-bed thermocline system is regarded as a promising cost-effective TES option, it still has some shortcomings. During the operation, the thermocline region gradually increases, and the loss of stratification in two levels of temperature leads to the system with more useless energy for feeding the power block. Moreover, the thermocline region could be locally destroyed due to the presence of local disturbances and natural convections induced by the heat loss through the tank wall [5] resulting in mixing of hot and cold molten salt. The degradation of the thermocline region will reduce both the energy efficiency and the operational stability of the storage system. Especially, to overcome complicated solar fluctuations in unfavorable weathers, the thermocline storage system may need to be charged and discharged frequently during the daytime. Frequent charge and discharge of the thermocline storage system may not only intensify the thermocline expansion, but also induce more loss of stratification due to the presence of more local disturbances, both of which significantly aggravate the thermocline degradation. Moreover, a CSP plant incorporating only a thermocline TES system can hardly cope with frequent solar fluctuations as flexibly as a plant with a two-tank TES system.

To overcome these problems, a novel hybrid storage system integrating a big packed-bed thermocline tank and a small two-tank storage system is proposed in this paper. The big pack-bed thermocline tank guarantees a low cost of the hybrid storage system, and the utilization of the small two-tank system enables not only the avoidance of frequent charge–discharge of the thermocline tank during the daytime but also a flexible and stable operation of the whole CSP system in varying weather conditions. Detailed descriptions of the hybrid storage system along with the typical working modes are presented. And the transient thermal performance of the hybrid storage system under different weather conditions is numerically investigated based on the developed numerical model for the hybrid storage system.