Applied Thermal Engineering 48 (2012) 24–31

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Criteria for performance improvement of a molten salt thermocline storage system

Xiaoping Yang [a,b,*], Xiaoxi Yang [a], Jing Ding [c], Youyuan Shao [a], Frank G.F. Qin [a], Runhua Jiang [a]

[a] Guangdong Provincial Key Laboratory of Distributed Energy Systems, Dongguan University of Technology, Dongguan, China
[b] Key Laboratory of Enhanced Heat Transfer and Energy Conservation of the Ministry of Education, South China University of Technology, Guangzhou, China
[c] School of Engineering, Sun Yat-Sen University, Guangzhou, China

HIGHLIGHTS

► Four criteria for describing the performance of a molten salt thermocline thermal energy storage system are studied.
► The effects of the physical properties of different filler materials on performance are also discussed.
► Filler particles with a small diameter and low thermal conductivity can improve efficiency η_1.
► Filler particles with large volume-specific heat capacity and small porosity can increase thermal storage capacity.

ARTICLE INFO

Article history:
Received 30 September 2011
Accepted 20 April 2012
Available online 27 April 2012

Keywords:
Molten salt
Thermocline
Filler material
Performance

ABSTRACT

Thermal energy storage is considered to be an important subsystem for solar thermal power stations because of the fluctuations in sunshine over time. A molten salt thermal storage tank contains thermally stratified fluid, with hot temperature on the upper level and cold temperature in the lower level. Although a few studies have explored molten salt thermocline energy storage for solar thermal plants, the criteria for performance improvement are still not understood adequately. To this end, this paper summarizes four criteria for describing the performance of a molten salt thermocline energy storage system. The criteria emphasize different aspects of the storage process, including thermal storage capacity, entropy generation, efficiency η_1 based on outlet temperature, and efficiency η_2 based on thermocline thickness. The effects of the physical properties of different filler materials on the performance are also discussed. The findings indicate that filler particles with higher density, higher specific heat, lower diameter, lower thermal conductivity, and lower porosity should be selected to increase thermal storage capacity and efficiency. However, increasing the density and specific heat will also lead to higher entropy generation in the system.

1. Introduction

With the increasingly worsening problems related to energy crises, climate change, and other environmental issues, experts and authorities agree that the development and utilization of new and renewable energy have become issues of serious concern [1]. Exhaust gases, dust, and fumes emitted by solar electric generation systems (SEGS) cause minimal pollution. Most importantly, these systems do not emit carbon dioxide (the greenhouse gas primarily responsible for global climate change) during operation. Hence, an SEGS has huge potential as a renewable energy source.

The output of a simple solar-only power plant depends strongly on solar input, which may or may not correspond closely with the load profile of a utility company. Thermal energy storage (TES) can be used to store energy for delivery at a later time, or to facilitate the generation of plant output during intermittent cloudy weather conditions. To improve power generation efficiency, reduce operational costs, and increase the stability and continuity of solar thermal systems, thermal storage equipment is needed to balance the mismatch between solar energy supply and electricity consumption [2–4].

A thermocline tank uses a single tank to store thermal energy. Inside the tank, a thermal gradient or thermocline separates the hot fluid from the cold fluid. The heat transfer fluid (HTF) maintains

* Corresponding author. Guangdong Provincial Key Laboratory of Distributed Energy Systems, Dongguan University of Technology, No.1 University Road, Songshan Lake, Dongguan, China. Tel./fax: +86 769 22861808.
E-mail address: 103194140@qq.com (X. Yang).

1359-4311/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.applthermaleng.2012.04.046

high and low temperatures above and between the thermocline, respectively. Generally, a low-cost filler material is used to displace higher-cost liquid. When the system is being charged, cold fluid is drawn from the bottom and then heated as it passes through a heat exchanger. The fluid then returns to the top of the tank. When the tank is discharged, hot fluid is drawn from the top and cooled as it passes through a heat exchanger. During the charging or discharging process, the thermocline moves up or down until it flows out of the tank. Another type of TES uses a two-tank system, wherein one of the tanks stores hot storage material and the other receives cold storage material. A two-tank system can be classified as a direct or indirect storage system. In a direct system, the HTF is directly stored in a hot tank for use during cloudy weather conditions or at night. The cooled HTF is pumped into the cold tank, where it remains until it is re-heated. In an indirect storage system, the energy is stored directly by a second storage material instead of by the HTF. A heat exchanger is required to transfer the energy from the HTF to the storage material or vice versa.

One of the advantages of a two-tank TES system is the separate storage of cold and hot storage materials, which makes the two-tank TES system a low-risk approach to energy storage. However, its disadvantage is the exorbitant cost of the material used as HTF and the storage materials. A single-tank TES requires investment that is only about 35% of that needed for a two-tank system. Nevertheless, ideal temperature stratification is difficult to achieve in the former because of the thermal convection of fluids. Thus, to reduce costs and enhance the thermocline effect, quartz, sand, or other materials are used in maintaining stratification in the tank [5].

Although many studies have focused on the thermal performance of packed-bed thermocline storage systems used for water or oil storage [6–9], few reports have focused on the packed-bed molten salt thermocline system. Pacheco et al. [10] analyzed a thermocline storage system for a trough solar power plant using molten salt as the heat transfer and storage medium. Through both numerical simulation and engineering-scale experiment, they found that a molten salt thermocline system is a feasible option for thermal storage and is about two-thirds the cost of a two-tank molten salt system for parabolic trough power plants. Zhen Yang et al. [11] analyzed the performance and discharge efficiency of a molten salt thermocline storage system. They developed a comprehensive, two-temperature model, and solved the governing equations using a finite-volume approach. Their study explored the thermal characteristics, including temperature profiles and discharge efficiency, and found the discharge efficiency to be improved at small Reynolds numbers and larger tank heights. Chao Xu et al. [12] also developed a comprehensive transient, two-dimensional, two-phase model for a packed-bed molten salt thermocline system. They examined various numerical results, including variations of the outlet molten salt temperature and thermocline thickness with discharging time and representative thermocline profiles.

The literature review shows that despite several studies on molten salt thermocline thermal energy storage, the thermal performance of the system is not yet well-understood. Criteria for evaluating the charge/discharge performance are needed, as well as guidelines for the selection of filler materials according to the criteria for thermocline thermal storage systems.

The present work includes numerical and experimental studies of a molten salt thermocline thermal energy storage system. The structure of the paper is organized as follows. The experimental description is first presented, and then the transient two-phase model formulation for heat transfer within the packed-bed thermocline system is introduced. Afterward, four factors for determining the performance of a molten salt thermocline storage system are summarized. The criteria emphasize different aspects of the storage process, including thermal storage capacity, entropy generation, efficiency η_1 based on outlet temperature, and efficiency η_2 based on thermocline thickness. The developed model is validated based on the experimental results. The key physical properties of the filler materials that influence system performance are compared in accordance with the evaluation criteria. Finally, some conclusions for selected materials are given.

2. Experimental setup

Fig. 1 presents the schematic diagram of the experimental system, which includes the molten salt tank, pump, molten salt furnace, thermocline storage tank, and data acquisition system. The experiments use composite nitrate salt as HTF. Molten salt is first heated to a specific temperature using an electric heater in the molten salt tank, then pumped through the flowmeter and V4 valve into the molten salt furnace if a higher experimental temperature is needed, and finally allowed to flow into the thermocline storage system to accomplish the thermal storage experiment. At the beginning of the charging process, the storage tank filled with solid filler material is in cold temperature, and then the hot molten salt enters the storage tank from the V9 valve at the top, transfers heat energy to the cold solid filler material, leaves the storage tank through the V10 valve with a lower temperature, and reflows into the molten salt tank.

The diameter and height of the thermal storage tank is 263 and 550 mm, respectively. A total of 12 thermocouples are used to measure the temperature of the HTF, two for the molten salt temperatures at the inlet and outlet of the thermocline storage tank, and the other ten for the molten salt temperatures at the middle of the thermocline storage tank. The distance between two thermocouples is 50 mm. The diameter of the filler particle is 30 mm, whereas the density of the filler material is 2100 kg/m^3.

All the pipes, valves, and the thermal storage tank are insulated with a 100 mm-thick asbestos sheet, and then covered with a polished aluminum sheet. The pictures of the experimental setup and thermocline storage tank filled with filler material are shown in Fig. 2a and b.

3. Model description

The charging process of a molten salt thermocline storage tank is also analyzed numerically. The physical model is shown in Fig. 3. The height and diameter of the storage tank is 2 and 1 m, respectively. At the initial time, the tank is filled with solid filler material with cold temperature (573 K), and then, when the charging process begins, molten salt with hot temperature (773 K) flows into the tank from the top inlet, transferring the heat to the filler

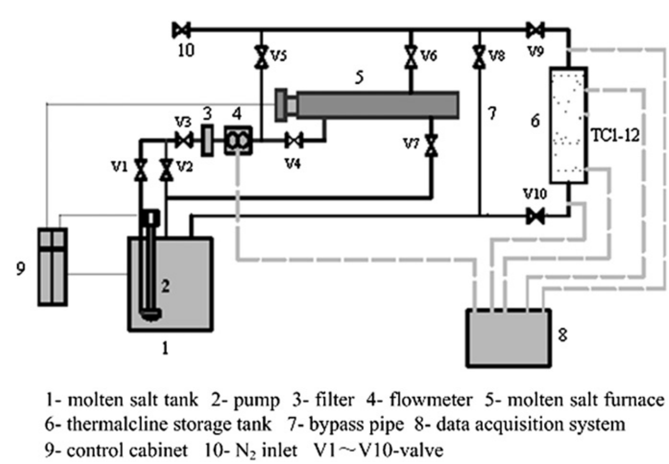

Fig. 1. Schematic of the experimental system.