Sensitivity analysis of the numerical study on the thermal performance of a packed-bed molten salt thermocline thermal storage system

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ABSTRACT

In this paper, a comprehensive transient, two-dimensional, two-phase model for heat transfer and fluid dynamics within the packed-bed molten salt thermocline thermal storage system is presented. After model validation, the developed model is used to investigate the general thermal behavior of a discharging process of the pack-bed thermocline system and evaluate the interstitial heat transfer coefficient, the effective thermal conductivity and effect of the thermal conductivity of solid fillers. The results show that the thermocline region is moving upward with slight expansion during the discharging process. With the use of two insulation layers, a uniform cross-sectional temperature distribution is well achieved. The use of different correlations for the interstitial heat transfer coefficient or the effective thermal conductivity from the literature leads to negligible difference in the predicted thermal performance. It is also found that decreasing the heat transfer rate between fluid and solid fillers, or increasing the thermal conductivity of solid fillers, results in an increase in the thermocline thickness which finally decreases the effective discharging time and the effective discharging efficiency.

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1. Introduction

Concentrating solar power (CSP) technologies which utilize inexhaustible and clean solar energy have been projected as one of the most promising candidates for substituting conventional power generation technologies [1–5]. Recently, rapid development occurred worldwide in basic technology and market strategy for CSP technologies including parabolic trough, power tower and dish/engine. However, as with most renewable energy systems, sunlight is available only in daylight hours which even in the best case is less than 50%, and it is still heavily influenced by clouds, aerosols, etc. To increase the availability beyond normal daylight hours, a thermal energy storage (TES) system which stores solar thermal energy for later use is usually incorporated in the CSP system. The TES system is a key performance advantage of the CSP technology, and it can significantly increase the hours of electricity generation and improve the dispatchability of CSP plants. Also, a low-cost TES system helps to reduce the levelized cost of electricity (LCOE) for CSP systems.

Different TES systems have been proposed and implemented in the past: oil, solid substances, saturated water and molten salt. Of these systems, molten salt offers the best balance of capacity, cost, efficiency and usability at high temperatures. Presently, TES

systems using molten salt are widely implemented or under development worldwide [6–12]. The molten salt TES systems can be generally categorized into two-tank system and one-tank thermocline system. The two-tank system has two tanks for storing the molten salt: one at high temperature and the other at low temperature. The two-tank molten salt system is the most proven utility-scale TES system, and it has been used or projected in many CSP plants including the 10 MW Solar Two tower plant in America, the Andasol (1-3) parabolic trough power plant (50 MW per plant) in Spain and the 280 MW Solana parabolic trough power plant in America [7,8,13].

The one-tank system only has one storage tank, within which a portion of the medium is at high temperature and a portion is at low temperature. The high- and low-temperature regions are separated by a temperature gradient or thermocline. During the charging process, high-temperature fluid from the solar receiver enters the top of the tank and exits the bottom at low temperature. Accordingly, the thermocline moves downward and thermal energy is stored in the high-temperature region. During the discharging process, the molten salt flows reversely and the thermocline moves upward. Compared to the two-tank system, the one-tank thermocline system requires only one storage tank, and low-cost solid storage medium can be used in the tank to replace part of the molten salt (referred to packed-bed thermocline), which can effectively reduces the cost of TES system by 20–37% [6]. Due to the benefit of low cost, the packed-bed thermocline system has

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Nomenclature

C_F	inertial coefficient	*Greek*	
c_p	specific heat capacity, J kg^{-1} T^{-1}	ε	porosity of packed-bed region
D	diameter of the storage tank, m	η	efficiency
d_p	diameter of the particle filler, m	μ	viscosity, kg m^{-1} s^{-1}
g	acceleration due to gravity, m s^{-2}	Γ	effective thermal conductivity, W m^{-1} K^{-1}
H	tank height, m	ρ	density, kg m^{-3}
h_v	interstitial heat transfer coefficient, W m^{-3} K^{-1}		
K	permeability of porous material, m^2	*Subscripts*	
k	thermal conductivity, W m^{-1} K^{-1}	*crit*	critical value
L	length, m	*d*	discharging
$\dot{m}$	mass flow rate, kg s^{-1}	*eff*	effective value
Nu	Nusselt number	*h*	hot fluid
p	pressure, Pa	*i*	insulation layer 1, tank steel wall, and insulation layer 2
Pr	Prandtl number	*in*	inlet
Re	Reynolds number	*in*1	insulation layer 1
r	radius, m	*in*2	insulation layer 2
T	temperature, K	*l*	liquid molten salt; cold fluid
t	time, s	*ms*	molten salt
V	tank volume, m^3	*out*	outlet
u	velocity, m s^{-1}	*s*	solid fillers
x	location along the axis of the tank, m	*st*	stainless steel

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attracted more and more attention. A small pilot-scale (2.3 MWh t) packed-bed molten salt thermocline system has been successfully demonstrated in Sandia National Laboratories [11]. Quartzite rocks and sands were chosen as the low-cost solid fillers which provided the bulk of thermal capacitance of the thermal storage [14]. Zuo and Li [15] developed a molten salt thermocline system combining with two storage subsystems using phase change materials at the top and bottom of the tank.

However, large-scale utilization of the packed-bed thermocline system is still hindered by several technical problems. For instance, the thermocline region is prone to expanding with time or degrading after several charging–discharging cycles. To overcome these problems, it is essential to gain a comprehensive understanding about the operation process of the system and the related inherent-coupled heat and mass transport mechanisms. Since many important parameters are associated with the development process of this system, numerical investigations have been needed to minimize the expensive and time-consuming experimental investigations.

Although great efforts have been focused on the numerical investigations of thermal performance of the packed-bed thermocline system using water or oil as the fluid [16–25], little work has been reported about the numerical investigations of the packed-bed molten salt thermocline system [6,25–28]. Pacheco et al. [26] carried out a simple numerical investigation of the thermal behavior of the packed-bed molten salt thermocline system. The one-dimensional Schumann equations which involved several assumptions and simplifications were used in the modeling of heat transport between molten salt and solid fillers. Researchers in the National Renewable Energy Laboratory (NREL) [6] numerically modeled the packed-bed molten salt thermocline system in which the solid fillers were in the form of hexagonal rods or a honeycomb-like structure. Adiabatic boundary conditions were adopted when studying the core region of the tank. Yang and Garimella [27,28] developed a comprehensive two-temperature model to systematically investigate the discharging behavior of a packed-bed molten salt thermocline system. The effects of several parameters including tank height, molten-salt flow rate, and filler particle size on the thermal behavior were investigated. The effects of heat losses to the ambient air were also explored by employing non-adiabatic thermal boundary conditions with different heat transfer coefficients. Most recently, Lew et al. [25] numerically investigated the packed-bed thermocline system using the modified one-dimensional Schumann equations. Design procedures of the system were also discussed using the numerical modeling tool.

From the literature review, it can be seen that previous numerical investigations lack in a clear knowledge about the following two aspects: (1) the effects of some transport mechanisms, e.g., the two-dimensional thermal conduction between solid particles, have not been fully understood due to model simplifications; (2) various important constitutive correlations from the literature, e.g., the interstitial heat transfer coefficient between molten salt and solid fillers and the effective thermal conductivities of molten salt and solid fillers, have not been evaluated. Accordingly, this study aims at developing a comprehensive transient, two-dimensional, two-phase model for the packed-bed molten salt thermocline system with evaluations on various transport mechanisms and constitutive correlations. The rest of the paper is organized as follows. The transient two-dimensional two-phase model formulation for heat transfer and fluid dynamics within the packed-bed thermocline system will be first presented, and various constitutive correlations in the literature will be summarized. Then, the developed model will be validated based on the experimental results in the literature. The results and discussion will be shown for various aspects including the general thermal behavior, evaluations on the interstitial heat transfer coefficient and the effective thermal conductivity, and the effect of the thermal conductivity of solid fillers. Finally, some conclusions will be given.

2. Present model description

2.1. Governing equations

The general layout of the thermocline storage system is illustrated in Fig. 1a, which is similar to Yang et al.'s work [27–29]. As can be seen, the thermocline storage system mainly composes of a vertically standing cylindrical tank and the contained storage material, i.e., the molten salt and solid fillers. The tank has inlet/exit ports on the top and bottom for the flow of hot and cold molten salt,