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Thermal storage performance of molten salt thermocline system with packed phase change bed ☆

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ABSTRACT

Comprehensive transient and two-dimensional numerical model is developed to study energy storage performance of molten salt thermocline thermal storage system with packed phase change bed in solar thermal power. The results show that the packed phase change bed can remarkably increase the effective discharging energy and discharging efficiency. Because of phase change material, the thermocline can be divided into three stages including the high temperature thermocline, low temperature thermocline and phase change layer. As the melting point within the inlet and initial temperature increases, the whole discharging time decreases, while the effective discharging energy remarkably increases, and thus the melting point of phase change material should be within the initial temperature and effective outlet temperature for good heat storage performance. As the phase change material content increases, the effective discharging energy increases with the effective discharging time rising, and the effective discharging efficiency also increases.

1. Introduction

Concentrating solar power (CSP) [1,2] has recently been a very promising and challenging energy technology. Since solar energy is discontinuous, the thermal energy storage (TES) [3] is the key technology for solar thermal power system, and it can remarkably increase the effective electricity output hours and benefit the system stability. Molten salts are very important heat transfer and storage media at high temperature in solar thermal plants, chemical engineering and nuclear heat source, and the molten salt thermal storage system [4] is widely used in concentrating solar power for large operating temperature range and high heat capacity. The two-tank system [5,6] is the most widely used energy storage technology for solar thermal power, and it normally has one high temperature tank and one low temperature tank. Compared with the two-tank system, the one-tank thermocline system [7] is a more promising technology for low cost, and the high temperature and low temperature molten salt regions are separated by the thermocline. Till now, the two tank system has been demonstrated in many concentrating solar power plants in America and Spain, while the thermocline system need to be further developed.

The heat storage characteristics of molten salt thermocline system have been experimentally studied in some literatures. Pacheco et al. [8] first demonstrated and investigated packed-bed molten salt thermocline system with 2.3 MW h in Sandia National Laboratories. Brosseau et al. [9] suggested that quartzite rocks and sands were the low-cost and efficient solid fillers for packed bed. Zuo and Li [10] proposed a molten-salt hybrid thermocline thermal storage system with two storage subsystems using phase change materials at the top and bottom of the tank. Yang et al. [11] established an experimental system of thermocline thermal storage system, and measured the temperature evolution.

Based on the experimental results, many researchers numerically investigated the heat transfer and storage performance of molten salt thermocline storage. Lew et al. [12] numerically analyzed transient heat delivery and storage process in a thermocline heat storage system using the modified one-dimensional Schumann equation. Yang et al. [13] simulated molten-salt thermal energy storage in thermocline under different environmental boundary conditions. Xu et al. [14] numerically studied the thermal performance of a packed-bed molten salt thermocline thermal storage system, and mainly considered the heat transfer between solid and liquid phases. Nithyanandam et al. [15] investigated the latent thermocline storage system with encapsulated phase change material by assuming uniform flow velocity. Peng et al. [16] used the numerical concentric dispersion model to study the thermal performance of PCM-based high temperature thermal energy storage in packed bed during charging process. Meanwhile,

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Nomenclature

C_F	inertial coefficient (–)
c_p	thermal capacity (J kg^{-1} K^{-1})
d	particle diameter of the bed (m)
E	energy (MW h)
f	content (–)
g	gravitational acceleration constant (m s^{-2})
H	tank height (m)
h	heat transfer coefficient (W m^{-2} K^{-1})
h_{sl}	latent heat (J kg^{-1})
K	intrinsic permeability of the porous medium (m^2)
k	thermal conductivity (W m^{-1} K^{-1})
p	pressure (Pa)
q	heat flux (W m^{-2})
R	radius (m)
S	section area (m^2)
S_m	momentum source term (Pa/s)
S_e	volumetric energy source term caused by heat transfer (W m^{-3})
S_p	volumetric energy source term caused by phase change (W m^{-3})
T	temperature (°C)
T_m	melting point (°C)
t	time (s)
u	velocity (m/s)
V	volume (m^3)
y	coordinate (m)

Greek symbols

ρ	density (kg m^{-3})
ε	porosity (–)
η	efficiency (–)
μ	viscosity (kg m^{-1} s^{-1})

Subscripts

a	ambient condition
c	ceramic material
eff	effective
f	fluid phase
in	inlet
ini	initial condition
ins	insulation
l	liquid
out	outlet
p	phase change material
s	solid phase
tot	total energy storage, whole discharging process

Powell and Edgar [17] proposed an adaptive-grid model to simulate the storage performance of the thermocline thermal energy storage system.

Since the phase change material has high energy storage density during phase change process, the molten salt thermocline thermal storage system with packed phase change bed is expected to have good heat storage performance. In this paper, the heat transfer and storage performance of thermocline storage with packed phase change bed is numerically investigated using comprehensive transient and two-dimensional numerical model. The structure of the thermocline in packed phase change bed is analyzed, and the effective energy storage and discharging efficiency are studied under different melting point and phase change material content.

2. Numerical model

2.1. System description

The molten salt thermocline thermal storage system with packed phase change bed is a cylindrical tank that contains storage material, as illustrated in Fig. 1. The cylinder tank has an inlet and an outlet on the bottom and top for the hot and cold molten salt. The storage material includes molten salt and packed bed. In order to increase the energy storage density, the bed is packed by sphere that contains ceramic and phase change material [11], and the porosity and particle diameter of the bed are ε and d. Outside the cylinder tank, the insulation layer is normally used to reduce the heat loss.

The basic operating process of thermocline thermal storage system includes the charging and discharging processes. During the charging process, the cold molten salt in the tank is pushed by hot molten salt from solar heat receiver, and the cold packed bed is heated by the hot molten salt. As a result, the solar thermal energy from the receiver can be stored in the tank. During the discharging process, the cold molten salt enters the tank from the bottom, and the hot molten salt in the tank and the molten salt heated by the hot packed bed is pushed out.

The experimental protocol of the present system can mostly refer to that of available molten salt thermocline system reported by Pacheco et al. [8], and their main difference is porous media in the cylindrical tank. In the present article, porous media is packed by ceramic sphere with encapsulated phase change material. The preparation method of ceramic heat storage sphere with encapsulated phase change material can refer to the patent [24], and it mainly includes three stages: (1) preparation of ceramic spherical shell with an outer hole; (2) preparation of encapsulants; (3) the encapsulation process with phase change material.

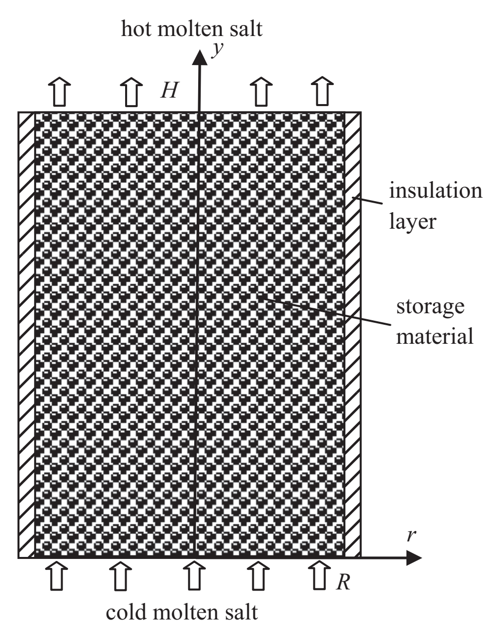

Fig. 1. The structure of molten salt thermocline thermal storage system.