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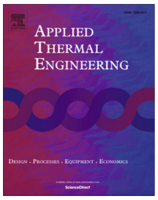

Research Paper

Thermocline characteristics of molten-salt thermal energy storage in porous packed-bed tank

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HIGHLIGHTS

- Molten-salt heat storage in porous packed-bed tank is simulated.
- Local thermal equilibrium theory is applicable for thermocline heat storage.
- Stable thermocline layers form during the heat storage or heat release processes.
- Heat storage efficiency is affected by the thermocline and porous filler.
- The porous filler with larger volumetric heat capacity is favorable.

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ABSTRACT

Based on the local thermal equilibrium theory in porous media, a two-dimensional numerical model is developed to investigate the heat storage and heat release processes of a molten-salt thermocline in a porous packed-bed tank. The numerical model is validated by comparing the simulation results with the experimental data. The performance of the heat storage system is analyzed using the thermocline thickness and the heat storage efficiency with a focus on energy balance. The results show that stable thermocline layers can form during heat storage or heat release processes. Because of the existence of the thermocline and replaced porous fillers, the heat storage efficiency in a porous packed-bed tank is slightly lower than that of pure molten-salt thermocline heat storage. The volumetric heat capacity of porous media is a key factor in heat storage performance. Improving the performance of the porous filler and setting the condition of a reasonably low flow rate, it can enable optimization control of the thermocline evolution in heat storage/release processes and improve the thermal efficiency of the heat storage system, which reveals directions for further research.

1. Introduction

Concentrated solar power (CSP) plants have attracted increasing interest from researchers and governments throughout the world in recent years. The high-temperature heat transfer and storage process is pivotal for the improved efficiency of the light-heat-electricity system. The two-tank molten-salt heat storage is the current main method that is used in solar heat storage technologies [1], but the unit investment cost and operating cost are relatively high due to larger amounts of container materials and molten salts and higher high-temperature management expenses. To reduce the fixed investment cost, a small pilot-scale (2.3 MW h) thermocline indirect storage system was developed and tested by Pacheco et al. [2], and the cost was approximately 2/3 of the cost in a two-tank molten salt system for parabolic trough power plants. Based on this successful experience, many scholars have conducted research studies on thermocline heat storage and consider it one of the most promising options for reducing the levelized electricity costs in solar thermal power plants with a storage system [3,4]. Due to thermocline degradation, the annual electricity yield of a plant with thermocline storage is always less than that of the same plant with a two-tank storage system. Biencinto et al. [5] published an annual performance analysis for different charge and discharge operation strategies to identify the operation mode that minimizes the difference in the annual yield between both systems. The results created a useful guideline for further economic assessments associated with thermocline heat storage systems.

In experimental research on molten-salt thermocline heat storage, it is difficult to accurately measure parameters such as fluid

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temperature, fluid flux and pressure drop because of the variable thermal properties of molten salt and the limitations of measuring instruments and testing methods at high temperature. However, the research methods and simulation softwares used in computational fluid dynamics (CFD) can comprehensively simulate the fluid flow and heat transfer characteristics of a thermal energy storage (TES) system, which effectively addresses the deficiency of experimental techniques. Yang et al. [4] developed a comprehensive two-temperature model to investigate energy storage in a molten-salt thermocline, and thermal characteristics such as temperature profiles and discharge efficiency of the storage tank were systematically explored. Modi and Pérez-Segarra [6] presented a one-dimensional transient mathematical model for a single-tank thermocline TES system. The model used temperature-dependent correlations to obtain the thermophysical properties for the heat transfer fluid and considered heat loss through the tank wall. The results suggested that two important aspects in assessing the performance of the system were the cyclic behaviour of the system and the time required to attain equilibrium conditions. Bayón and Rojas [7] presented a single-phase one-dimensional model known as CIEMAT1D1SF for characterization of the behaviour of thermocline tanks with an effective storage medium formed by either a liquid or the combination of a liquid and a packed bed. Maximum efficiency guideline plots for thermocline tanks with different storage media were presented for various temperature intervals. Votyakov and Bonanos [8] developed a new one-dimensional one-phase model to predict the performance of packed-bed thermocline TES tanks. The model was based on perturbation theory and the fact that the difference between the fluid and solid filler material temperatures is small. The perturbation model presented a significant improvement over the one-phase model used in other studies in the literature because it correctly predicted the importance of the diffusion term in the one-phase energy equation. The perturbation model was compared with the full two-phase model and notably good agreement was found. Flueckiger and Garimella [9] performed numerical simulation of a dual-media thermocline tank to investigate the effects of different granule diameters and non-adiabatic boundary conditions along the tank wall. The efficiency of the tank was measured in terms of molten-salt energy, exergy, and energy subject to an outflow temperature criterion. Xu et al. [10,11] developed a comprehensive transient, two-dimensional, two-phase model for heat transfer and fluid dynamics within a packed-bed molten-salt thermocline TES system. Based on the developed model, the effects of various parameters such as flow rate, inlet temperature of molten salt, porosity and height of the system, and thermal losses on the thermal performance of the system were investigated. The standby behaviour was also studied with a focus on the effects of wall structure, ambient air velocity on the thermocline expansion behaviour. This work offered a framework for interpreting the complicated thermocline behaviour and optimizing the system configurations and operational strategies of the packed-bed molten-salt thermocline TES system.

In the present paper, a two-dimensional numerical model is developed to investigate the heat storage/release processes of a molten-salt thermocline in a porous packed-bed tank. The heat storage performances are analyzed using the thermocline thickness and heat storage efficiency with a focus on energy balance.

2. Experimental setup and numerical model

2.1. System description

The authors designed a hybrid heat storage experimental system, as shown in Fig. 1. The primary loop system consists of a molten salt vessel, a molten salt pump, a filter, a flow meter, a molten salt furnace and an experimental heat storage device. The molten salt vessel is a large container of 3 m × 1.5 m × 2 m, and stores about eight tons of molten salt. The experimental heat storage device used in this research work is a single molten-salt tank. Its external diameter and height are 120 mm and 600 mm, respectively. The middle section of the tank is a thermocline sensible heat storage zone whose length is 450 mm. After heating and melting in the molten salt vessel, the molten salt is placed in the heat transfer pipeline by the high-temperature molten salt pump and flows through the filter, flow meter and experimental heat storage device in turn. If a working temperature of 550 °C is required, the molten salt can be further heated by the molten salt furnace. The fluid flow and heat storage performance of the molten salt in a single tank were experimentally investigated and reported in Ref. [12].

The geometrical model of a porous packed-bed tank is shown in Fig. 2. In the heat storage process, the tank initially contains a molten salt fluid with a low temperature T_0 and porous fillers. At the initial time $t = 0$, a uniform high-temperature molten salt fluid with temperature T_{in} and velocity u_{in} enters the tank from the upper end, and the existing low-temperature molten salt fluid in the tank flows out from the bottom end simultaneously. Similarly in the heat release process, the tank initially contains a high-temperature molten salt fluid with temperature T_0 and porous fillers. At the initial time $t = 0$, a uniform low-temperature molten salt fluid with temperature T_{in} and velocity u_{in} enters the tank from the bottom end, and the existing high-temperature molten salt fluid in the tank flows out from the upper end simultaneously.

2.2. Governing equations

The essential assumption for the porous media model in the FLUENT software is local thermal equilibrium in the porous media, which considers that the heat transfer between the fluid flow and the solid skeleton of porous media exists in thermal equilibrium. The packed bed with porous fillers is a continuous and homogeneous porous zone, and the molten salt flowing through the bed is laminar and incompressible. The study in Ref. [3] verified the validity of the local thermal equilibrium model applied in the simulation of thermocline heat storage. Therefore, the FLUENT software is used to perform numerical analysis of the thermocline heat storage/release processes in a porous packed-bed tank. Considering the variable thermal properties of the molten salt fluid and the transport characteristic of porous media, the governing equations can be identified based on the internal solvers of the FLUENT software. Because the heat storage system and the associated fluid flow and heat transfer processes are assumed to be axisymmetrical, the parameters in the circumferential direction are zero.

The porous media model in the FLUENT software incorporates an empirically determined flow resistance in a region of the model defined as “porous”. Porous media are modelled by the addition of a momentum source term to the standard fluid flow equations. The basic continuity and momentum equations can be described as shown in Refs. [13,14]:

$$\frac{\partial(\varepsilon\rho_f)}{\partial t} + \nabla\cdot(\rho_f\vec{u}) = 0 \tag{1}$$

$$\frac{\partial}{\varepsilon\partial t}(\rho_f\vec{u}) + \frac{1}{\varepsilon^2}\nabla\cdot(\rho_f\vec{u}\vec{u}) = \nabla\cdot(\mu\nabla\vec{u}) - \nabla p + \rho_f\vec{g} + S_m \tag{2}$$

where ρ_f, μ and u are the density, dynamic viscosity and velocity of fluid phase, respectively, ε is the porosity, g is the gravitational acceleration constant, and S_m is the momentum source term.

To recover the case of simple homogeneous porous media:

$$S_m = -\left(\frac{\mu}{\alpha}\vec{u} + \frac{C_F\rho}{2}|\vec{u}|\vec{u}\right) \tag{3}$$