



# Dynamic thermal performance analysis of a molten-salt packed-bed thermal energy storage system using PCM capsules



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## HIGHLIGHTS

- Dynamic thermal performance of a molten-salt packed-bed TES system using PCM capsules was investigated.
- The temperature response and phase change process within PCM capsules were revealed.
- A quasi-isothermal region and two thermocline regions were identified for the axial molten-salt temperature distribution.
- PCT of PCM, molten-salt inlet velocity and capsule diameter influence the effective discharging efficiency.

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## ABSTRACT

We investigate the dynamic thermal performance of a molten-salt packed-bed thermal energy storage (TES) system using capsules filled with high-temperature phase change material (PCM), which is identified as a promising low-cost TES system for concentrating solar power (CSP) plants. A transient two-dimensional dispersion-concentric (D-C) model is modified to account for the phase change process within capsules so as to determine the temperature distribution and phase change front within each capsule. Using the model, detailed characteristics of heat transfer between molten salt and the packed PCM capsules are investigated, and a parametric sensitivity analysis is provided. During the discharging process, different variation trends are found for the capsule temperature due to the existence of the isothermal solidification process. As a result, generally there exists a quasi-isothermal region and two thermocline regions for the molten-salt temperature along the tank height, and the molten-salt temperature at the outlet also shows a quasi-isothermal period, during which the molten-salt outlet temperature is very close to the phase change temperature (PCT) of PCM. It is also found that the effective discharging efficiency of the system can be increased by increasing the PCT, decreasing the molten-salt inlet velocity or decreasing the capsule diameter. These results provide suggestions to optimize the design and operational parameters for the system within practical constrains.

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## 1. Introduction

Low-cost and high-efficient TES technologies are vital for large-scale applications of CSP systems. With TES, CSP systems can not only generate stable and dispatchable electricity, but also achieve higher annual capacity factors via extending the generation duration. Presently, the two-tank molten-salt TES system is the only one that has been applied in large-scale commercialization, such as in the Andasol (1–3) parabolic trough power plants (50 MW per plant) and the Gemasolar tower plant (19.9 MW) in Spain

et al. Although the two-tank molten-salt TES technology is commercially applied, its relatively high cost and limited space for cost reduction make it undesirable for cost-effective CSP technologies in the future [1–3].

Different from the two-tank system, the one-tank thermocline TES system has only one storage tank, and the relatively expensive molten salt can also be partially replaced by relatively cheap packed solid fillers. Therefore, the one-tank packed-bed thermocline TES system offers a low-cost TES option and may save 35% of capital cost compared to the two-tank system [1]. In recent years, the packed-bed thermocline TES technology has gained increasing attentions worldwide [1–9]. The first pilot-scale molten-salt packed-bed thermocline tank for parabolic trough power

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## Nomenclature

$C_F$	inertial coefficient	<i>Greek</i>	
$C_p$	specific heat capacity, $\text{J kg}^{-1} \text{K}^{-1}$	$\alpha$	thermal diffusivity, $\text{m}^2 \text{s}^{-1}$
$D$	diameter of the storage tank, m	$\beta$	thermal expansion coefficient, $\text{K}^{-1}$
$d_p$	spherical capsule diameter, m	$\gamma$	kinematic viscosity, $\text{m}^2 \text{s}^{-1}$
$g$	acceleration due to gravity, $\text{m s}^{-2}$	$\varepsilon$	porosity of packed-bed region
$H$	tank height, m	$\mu$	viscosity, $\text{kg m}^{-1} \text{s}^{-1}$
$h$	heat transfer coefficient, $\text{W m}^{-2} \text{K}^{-1}$	$\rho$	density, $\text{kg m}^{-3}$
$h_{\text{pcm,sl}}$	enthalpy of PCM, $\text{J kg}^{-1}$	$\Gamma$	effective thermal conductivity, $\text{W m}^{-1} \text{K}^{-1}$
$h_p$	heat transfer coefficient at the capsule surface, $\text{W m}^{-2} \text{K}^{-1}$	$\xi$	radial coordinate inside each capsule
$h_v$	volumetric interstitial heat transfer coefficient, $\text{W m}^{-3} \text{K}^{-1}$	$\eta$	effective discharging efficiency
$K$	intrinsic permeability of porous medium, $\text{m}^2$	<i>Subscripts</i>	
$k$	Thermal conductivity, $\text{W m}^{-1} \text{K}^{-1}$	l	molten salt
$l$	length, m	d	discharging
$Nu$	Nusselt number	eff	effective value
$p$	pressure, Pa	i	insulation layer 1, tank steel wall and insulation layer 2
$Pr$	Prandtl number	in	inlet
$Ra$	Rayleigh number	in1	insulation layer 1
$Re$	Reynolds number	in2	insulation layer 2
$r$	radius, m	ms	molten salt
$T$	temperature, K	out	outlet
$t$	time, s	p	PCM
$u$	velocity, $\text{m s}^{-1}$	R	radius
$x$	location along the axis of the tank, m	st	stainless steel

plants was built and tested in Sandia National Laboratories [4]. It was shown that silica sand and quartzite rock were compatible with nitrate salts and thus were chosen as the most practical filler materials. Valmiki et al. [5] presented an experimental study of the heat transfer of thermal energy charging and discharging in a lab-scale packed-bed thermocline TES tank. The experimental data provide a basis for the validation of mathematical models of thermocline storage system for CSP plants.

Compared to the little experimental research, many numerical investigations about the packed-bed thermocline TES system for CSP plants were reported in the past years. Yang and Garimella [6,7] carried out a series of numerical investigations on the molten-salt packed-bed thermocline system using the developed two-temperature model. Li et al. [9] presented dimensionless heat transfer governing equations for fluid and solid fillers for the packed-bed thermocline TES and studied various scenarios of thermal energy charging and discharging processes. Recently, Xu et al. [1,2,27] presented a transient two-dimensional two-phase model to investigate the discharging behavior of the packed-bed thermocline tank. A parametric analysis was carried out and various influencing factors were analyzed. A transient two-dimensional dispersion-concentric (D-C) model was also developed to investigate the characteristics of heat transfer within solid fillers for the discharging process [3].

Besides solid fillers, capsules filled with PCM are also very desirable to be used in packed-bed thermocline systems, because storing thermal energy in the form of latent heat provides the benefits of higher energy storage density which brings to smaller storage volume for a given storage capacity. Packed-bed TES systems with PCM capsules have been extensively studied both experimentally and numerically for low-temperature storage applications such as space and water heating, cooling and air-conditioning [10–23]. Nallusamy et al. [10] presented an experimental study on the thermal behavior of a packed-bed of combined sensible and latent heat

TES unit. Paraffin filled in spherical capsules was used as the PCM and water was used as the heat transfer fluid (HTF). Both constant and varying heat sources were tested in the charging and discharging processes. Bédécarrats et al. [11,12] presented an experimental investigation of the performance of a TES system packed by spherical capsules filled with water as the PCM. The effects of various parameters including the inlet HTF temperature and flow rate, kinetics of cooling and heating on the charging and discharging performance, were investigated. They also presented a numerical study to complement with these investigations.

Ismail and Henríquez [13] investigated the charging and discharging processes of a cold storage system packed by spherical capsules filled with water as the PCM. A simplified transient one-dimensional model was developed to investigate the effects of various geometrical and operational parameters. The solidification process inside a spherical capsule was simulated by the one-dimensional heat conduction model with phase change. Arkar and Medved [14] studied both numerically and experimentally a cylindrical TES tank containing spheres filled with paraffin for heating and cooling applications. The radially dependent bed porosity was considered in the model. The influence of the accuracy of the PCM thermal property on the predictions of thermal response was investigated. Regin et al. [15] numerically analyzed the thermal behavior of a packed-bed storage system filled with paraffin capsules for solar water heating application. The developed model used governing equations similar to those of Schumann, except that the phase change process inside of capsules was analyzed by using the enthalpy method. Xia et al. [16] proposed a numerical model for the packed-bed TES tank with PCM capsules. The flow field as the fluid flows through the voids of packed capsules as well as the thermal gradients inside of the PCM capsules was investigated. The effect of arrangement of the PCM capsules was also analyzed based on the model. Wu et al. [17] also presented a one-dimensional model to study the dynamic characteristics of

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