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# Stabilization of the outflow temperature of a packed-bed thermal energy storage by combining rocks with phase change materials

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## HIGHLIGHTS

- Encapsulated phase-change material (PCM) placed on top of packed-bed thermal storage.
- 1.3% of PCM by volume sufficient to stabilize outflow temperature during discharging.
- Charging–discharging efficiency not affected by addition of phase-change material.

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## ABSTRACT

A new thermal energy storage (TES) configuration for concentrated solar thermal power is proposed for stabilizing the outflow temperature of a packed bed of rocks during discharging. This concept is based on the combination of sensible and latent heat storage by adding a relatively small amount of phase change material (PCM) to the top of the bed. Transient simulations solving the energy conservation equations for fluid, solid, and molten phases show that the outflow temperature during discharging can be kept constant around the PCM melting temperature, thereby eliminating the inherent temperature drop of TES based on sensible heat storage only. A PCM volume of only 1.33% of the total storage volume is sufficient to accomplish stabilization, corresponding to 4.4% of the total thermal energy stored as latent heat.



## 1. Introduction

For concentrated solar power (CSP) plants operating with air as the heat transfer fluid [1], thermal energy storage (TES) using a packed bed of rocks has been shown to offer a simple and efficient technical solution for overcoming the intermittency of solar radiation [2–5]. An inherent disadvantage of the batch-type sensible heat storage is the drop of the outflow air temperature toward the end of discharge period. This, in turn, complicates the integration with the downstream application requiring steady-state conditions, e.g., a Rankine or a Brayton cycle, or a thermochemical process. Latent heat storage, on the other hand, can store and release thermal energy at constant temperature, but suffers from relatively low efficiency for large temperature ranges [6]. Here, we propose a concept that combines the advantages of the sensible and latent heat storages while alleviating the critical issues incurred when using them separately. Specifically, we propose to add a limited amount of encapsulated phase change material (PCM) to the top of the packed bed of rocks as depicted in Fig. 1. During charging, hot air enters the TES from the top, transfers heat to the PCM and rocks, and exits at the bottom. During discharging the flow is reversed: air enters from the bottom, is heated by the rocks and PCM, and exits at the top. The direction of the flow exploits buoyancy forces to create and maintain thermal stratification, with the hottest region at the top of the storage. As will be shown in the analysis that follows, the proposed combination of sensible and latent heat stabilizes the outflow air temperature around the PCM's melting point.

## 2. Modeling

The heat transfer model is formulated for the two sections of the TES, namely sensible and latent heat sections, which are coupled by

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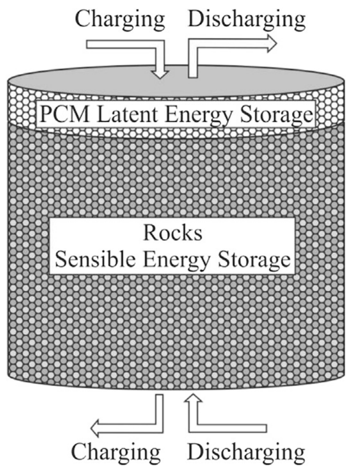


**Fig. 1.** Scheme of the combined sensible and latent heat concept for thermal energy storage, comprising a packed bed of rocks and phase change material.

the conditions of the air flow at their interface (e.g., $h_{f,out,PCM} = h_{f,in,rocks}$ for the charging phase).

### 2.1. Sensible heat section

The sensible heat section of the TES, i.e., the packed bed of rocks, is simulated using the 1D dynamic heat transfer model developed by Zanganeh et al. [2] cast in finite-volume form. The model considers separate fluid and solid phases with variable thermophysical properties and axial dispersion by conduction and radiation. The governing equations are:

Fluid:

$$\varepsilon\rho_f \frac{de_f}{dt} = \frac{A\varepsilon}{V}\left[\left(u\rho_f h_f\right)_{in} - \left(u\rho_f h_f\right)_{out}\right] + h_v\left(T_s - T_f\right) \quad (1)$$

Solid:

$$(1-\varepsilon)\rho_s \frac{de_s}{dt} = h_v\left(T_f - T_s\right) + \frac{A}{V}\left[\left(k_{eff}\frac{dT_s}{dx}\right)_{out} - \left(k_{eff}\frac{dT_s}{dx}\right)_{in}\right] \quad (2)$$

where all symbols are defined in the nomenclature. Physical properties and heat transfer correlations are listed in Ref. [2].

### 2.2. Latent heat section

The latent heat section of the TES, i.e., the top layer containing encapsulated PCM, is modeled following the approach of Beasley et al. [7]. The model considers separate fluid and solid phases. PCM properties are assumed to be independent of temperature. The governing equations are:

Fluid:

$$\varepsilon\rho_f \frac{de_f}{dt} = \frac{A\varepsilon}{V}\left[\left(u\rho_f h_f\right)_{in} - \left(u\rho_f h_f\right)_{out}\right] + h_{v,eff,PCM}\left(T_{PCM} - T_f\right) + \frac{A\varepsilon}{V}\left[\left(k_{eff,PCM}\frac{dT_f}{dx}\right)_{out} - \left(k_{eff,PCM}\frac{dT_f}{dx}\right)_{in}\right] \quad (3)$$

PCM:

$$\text{Solid phase: } (1-\varepsilon)(\rho c)_{eff,solid}\frac{dT_{PCM}}{dt} = h_{v,eff,PCM}\left(T_f - T_{PCM}\right) \quad (4)$$

$$\text{Two-phase: } (1-\varepsilon)(\rho h)_{eff,fus}\frac{d\chi}{dt} = h_{v,eff,PCM}\left(T_f - T_{PCM}\right) \quad (5)$$

$$\text{Liquid phase: } (1-\varepsilon)(\rho c)_{eff,liquid}\frac{dT_{PCM}}{dt} = h_{v,eff,PCM}\left(T_f - T_{PCM}\right) \quad (6)$$

where $\chi$ is the PCM's quality, i.e. the fraction of molten material, that ranges from 0 to 1. For simplicity, the encapsulation material is not considered separately. Instead, its properties are incorporated into effective properties of the encapsulated PCM using the average volumetric heat capacity of the PCM and the encapsulation,

$$(\rho c)_{eff} = \frac{\rho_{PCM}c_{PCM}V_{PCM} + \rho_{enc}c_{enc}V_{enc}}{V_{total}} \quad (7)$$

When both phases are present, only the PCM properties are considered since the encapsulation does not contribute to the latent energy storage,

$$(\rho h)_{eff,fus} = \frac{\rho_{PCM}h_{fus}V_{PCM}}{V_{total}} \quad (8)$$

The numerical solution method is analogous to that used for the sensible heat section. The convective heat transfer coefficient is calculated using the correlation of Galloway and Sage [8] with parameters determined from data measured by Beasley and Clark [9],

$$\mathrm{Nu}_{PCM} = 2 + 2.03\mathrm{Re}_0^{1/2}\mathrm{Pr}^{1/3} + 0.049\mathrm{Re}_0\mathrm{Pr}^{1/2} \quad (9)$$

and adjusted to consider the intra-particle conduction [10] with

$$h_{p,eff,PCM} = \frac{h_{p,PCM}}{1 + 0.25\mathrm{Bi}} \quad (10)$$

This adjustment is also adopted in the sensible heat model. The particle and volumetric convective heat transfer coefficients are related through $h_{v,eff,PCM} = h_{p,eff,PCM}6(1-\varepsilon)/d_{PCM}$. The effective thermal conductivity is given by Ref. [11]

$$\mathrm{Pe}_{eff} = \frac{\mathrm{Pe}_0}{0.5\mathrm{Pe}_0 + \frac{k_{eff}^0}{k_f}} \quad (11)$$

Grid-refinement studies were carried out for the sensible and latent heat sections. Grid spacings of 0.05 m and 0.01 m, respectively, were found to give good accuracy.

**Table 1**
Dimensions and properties of the reference case used for the validation of the model of the latent heat section of the TES.

| PCM properties | | Dimensions and operating conditions | |
|---|---|---|---|
| $c_{PCM, solid}$ [J/kg K] | 8374[a] | $D_{tank}$ [m] | 0.208 |
| $c_{PCM, liquid}$ [J/kg K] | 2093 | $H_{tank}$ [m] | 0.278 |
| $\rho_{PCM}$ [kg/m$^3$] | 812 | $d_{PCM}$ [m] | 0.02 |
| $h_{fus}$ [kJ/kg] | 197.6 | $\varepsilon$ [−] | 0.369 |
| $k_{PCM}$ [W/m K] | 0.24 | $\dot{m}_{charging}$ [kg/s] | 0.0328 |
| $T_{melt}$ [°C] | 50 | $T_{charging}$ [°C] | 59.5 |

[a] The high value of the specific heat of the PCM in the solid phase is ascribed to crystal transitions prior to melting [7].