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# Analysis and optimization of a latent thermal energy storage system with embedded heat pipes

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ABSTRACT

Latent thermal energy storage system (LTES) is an integral part of concentrating solar power (CSP) plants for storing sun's energy during its intermittent diurnal availability in the form of latent heat of a phase change material (PCM). The advantages of an LTES include its isothermal operation and high energy storage density, while the low thermal conductivity of the PCM used in LTES poses a significant disadvantage due to the reduction in the rate at which the PCM can be melted (charging) or solidified (discharging). The present study considers an approach to reducing the thermal resistance of LTES through embedding heat pipes to augment the energy transfer from the heat transfer fluid (HTF) to the PCM. Using a thermal resistance network model of a shell and tube LTES with embedded heat pipes, detailed parametric studies are carried out to assess the influence of the heat pipe and the LTES geometric and operational parameters on the performance of the system during charging and discharging. The physical model is coupled with a numerical optimization method to identify the design and operating parameters of the heat pipe embedded LTES system that maximizes energy transferred, energy transfer rate and effectiveness.


## 1. Introduction

Concentrating solar power (CSP) plants harness solar energy from the sun and store as heat, which can be used to drive a turbine in a power plant to generate electricity. CSP plants thus provide low-cost energy generation and have the potential to become the leading source of renewable energy for future power generation. Although energy from the sun is clean and abundant, the intermittent nature of solar availability makes it necessary to capture and store energy when available and discharge the energy on demand. Latent thermal energy storage (LTES) is the desired form of storing energy in a CSP plant due to its isothermal operation, high Rankine cycle efficiency, high latent heat of fusion and high volumetric energy density [1–4]. The latent heat of fusion and the volumetric energy density of the PCM are higher compared to the specific heat of PCM. For instance, the energy required to melt 1 kg of $KNO_3$ (latent heat) is 95 times higher compared to the energy required to raise the temperature of 1 kg of $KNO_3$ by 1 K (sensible heat). Thus, LTES requires a smaller volume of PCM to store energy and, in turn, offers compact energy storage advantage over a sensible energy storage counterpart.

The working of a LTES involves the exchange of energy between the HTF and the PCM through one of two processes namely, charging and discharging. During charging, the parabolic trough collector of a CSP plant focuses the solar energy to heat the HTF, which is flowed along the LTES compartment housing a solid PCM causing it to melt at a constant temperature, thereby resulting in energy storage through latent heat. During discharging, cold HTF flows through LTES compartment containing PCM in a molten state causing heat transfer from the PCM to the HTF resulting in the solidification of the PCM and a heated HTF, which may then be used to run the turbine of a power plant to generate electricity. Charging takes place during the day when solar energy is available while discharging occurs whenever the sun's energy is unavailable or when there is a peak demand in electricity. Several studies on the performance of LTES have suggested that the melting of a PCM in LTES (charging) is convection dominated due to the presence of free convection currents in the LTES whereas the solidification of PCM (discharging) is conduction dominated [5–8].

A fundamental challenge with LTES systems, however, is the low thermal conductivity of the PCM used, which reduces the rate of heat transfer. Several approaches to reduce the thermal resistance within the PCM are reported in the literature. Jegadheeswaran and Pohekar [9] presented a brief review of the literature over the past decade on enhancing the performance of LTES. Extended surfaces such as fins are commonly used to provide additional heat transfer area for heat transfer in thermal energy storage systems [10,11]. A technique of layering different PCMs in the order of decreasing melting temperatures along the HTF flow direction has also been analyzed in order to maintain constant heat flux to the PCM [12,13]. Other techniques include the impregnation of a

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**Nomenclature**

| | |
|---|---|
| $A$ | area, $m^2$ |
| $b$ | thickness, m |
| $c_p$ | specific heat, J/kg K |
| $E$ | thermal element |
| $h$ | convective heat transfer coefficient, $W/m^2$ K |
| HHP | horizontal heat pipe |
| $\Delta H_f$ | latent heat of fusion of PCM, J/kg |
| $k$ | thermal conductivity, W/m K |
| $\dot{m}$ | mass flow rate, kg/s |
| $\ell_i$ | thermal element length in the direction of heat transfer, m |
| $L$ | length, m |
| $Pr$ | Prandtl number |
| $Q_C$ | energy stored in the LTES with heat pipes, J |
| $Q_D$ | energy discharged from LTES with heat pipes, J |
| $Q_{C,0}$ | energy stored in the LTES without heat pipes, J |
| $Q_{D,0}$ | energy discharged from LTES without heat pipes, J |
| $Q_t$ | energy stored (discharged) near the tube, J |
| $Q_{HP}$ | energy stored (discharged) near heat pipes, J |
| $r$ | radius, m |
| $R_i$ | thermal resistance, K/W |
| $Ra$ | Rayleigh number |
| $Re$ | Reynolds number |
| $r$ | radial location, m |
| $s$ | melt or solid front location, m |
| $S_L$ | width of the module, m |
| $S_T$ | height of the module, m |
| $T$ | temperature, K |
| $T_m$ | melting temperature, K |
| $t$ | time, s |
| $V$ | volume, $m^3$ |
| VHP | vertical heat pipe |

*Subscripts and superscripts*

| | |
|---|---|
| $a$ | adiabatic |
| $c$ | condenser |
| $C$ | charging |
| $D$ | discharging |
| $e$ | evaporator |
| HTF | heat transfer fluid |
| $HP$ | heat pipe |
| $i$ | element $i$ |
| $m$ | module |
| $nc$ | onset of natural convection |
| PCM | phase change material |
| $t$ | tube |
| $w$ | wick |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | thermal diffusivity, $m^2/s$ |
| $\beta$ | thermal expansion coefficient, $K^{-1}$ |
| $\varepsilon$ | effectiveness |
| $\mu$ | dynamic viscosity, Pa s |
| $\rho$ | density, $kg/m^3$ |

porous structure formed of materials such as exfoliated graphite nanoplatelets [14,15] and dispersion of micro/nanoparticles within the PCM [16–18] to improve its thermal conductivity.

The use of embedded heat pipes or thermosyphons between the PCM and the HTF as a means of enhancing the thermal energy transport between them has also been explored: Horbaniuc et al. [19] reported on modeling of two-dimensional solidification of a low melting temperature PCM surrounding a longitudinally finned heat pipe, and investigated the duration of freezing as a function of the number of fins. Liu et al. [20] extended the work of Horbaniuc et al. using a circumferentially finned thermosyphon, to analyze the effect of HTF inlet temperature and the flow rate on the freezing rate of paraffin PCM. Lee et al. [21] used a thermosyphon to investigate its sensitivity on a variety of PCMs. Tardy and Sami [22] investigated numerically and experimentally the use of heat pipes to melt a low melting-temperature PCM and presented a thermal resistance model to determine the heat transfer rate with the HTF (air), and the associated melting process. Shabgard et al. [23] presented the use of embedded heat pipes in PCM for a LTES application.

This paper considers the system presented in [23] which incorporates heat pipes embedded between the HTF and the PCM to improve the overall energy storage and discharging rates of the system. The primary goals of the study are the following: (1) to elucidate the effects of the heat pipe and the LTES system geometry and the LTES operational parameters on the performance of the system during charging and discharging; to this end, a thermal resistance network model is utilized to describe the system during charging and discharging processes, and (2) using the physical model combined with a numerical optimization scheme, to determine the optimum design of the system for maximizing energy transferred, effectiveness, and energy transfer rate during charging and discharging processes individually as well as based on combined charging and discharging considerations. A further contribution is that while most of the studies in the literature have pertained to low temperature LTES, the present study focuses on a high temperature LTES system which is commonly found in CSP plants.

The paper is organized as follows: The mathematical model is described in the next section followed by a discussion of the optimization problem in Section 3. The results of the parametric studies and optimization are presented and discussed in Section 4.

## 2. Mathematical model

The LTES configuration considered in the study consists of a rectangular array of tubes of outer radius $r_t$ and tube wall thickness, $b_t$, arranged with a horizontal center-to-center spacing $S_L$ and a vertical center-to-center spacing $S_T$ and enclosed in a shell. Heat pipes are placed through the tube walls at $m$ (taken to be 4 in this study with two horizontally oriented and two vertically oriented heat pipes) circumferential locations and are spaced by a distance $L_m$ along the tube length. The periodic configuration of the heat-pipe-embedded tube-in-shell geometry allows for identification of a representative rectangular volume element of dimensions $S_T \times S_L \times L_m$ as shown in Fig. 1a for the analysis. Fig. 1a illustrates two different configurations based on the relative locations of the PCM and the HTF in the LTES. In Module 1, the HTF flows within the tube surrounded by the PCM, while in Module 2, the PCM is contained within the tube over which the HTF flows transverse to the tube axis. In both configurations, the heat pipes are placed in such a way that the interface of the evaporator and adiabatic sections of the heat pipe coincides with the wall of the tube in contact with the HTF to ensure that for a given design configuration, the surface area of the heat pipes exposed to the HTF remains the same in both modules. Fig. 1b shows a schematic of the longitudinal cross section of a heat pipe of radius $r_{HP}$ identifying the