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Design of a latent thermal energy storage system with embedded heat pipes

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HIGHLIGHTS

- Presents a novel system of latent thermal energy storage for concentrating solar power with embedded heat pipes.
- Presents a rigorous computational modeling of the system to elucidate its performance.
- Presents systematic analysis and optimal design of the thermal energy storage system.

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ABSTRACT

Thermal energy storage plays an important role in extending the operation of a concentrating solar power (CSP) plant to times when sufficient solar energy is unavailable for generation of electricity. Extending the CSP plant operation increases its capacity factor and can lead to reduction in the levelized cost of electricity equivalent to that of fossil-fueled power plants. In view of this, latent thermal energy storage (LTES) system embedded with gravity-assisted heat pipes is considered in the present study. Transient numerical simulations are presented and the influence of the design and operating parameters on the dynamic charge and discharge performance of the system is analyzed to identify operating windows that satisfy the U.S. Department of Energy SunShot Initiative targets, which include, storage cost less than \$15/kWh$_t$, round-trip exergetic efficiency greater than 95% and charge time less than 6 h for a minimum discharge period of 6 h. Overall, this study illustrates a methodology for design and optimization of LTES with embedded gravity assisted heat pipes (HP-TES) for a CSP plant operation.

1. Introduction

Concentrating solar power (CSP) technologies integrated with thermal energy storage (TES) have the ability to dispatch power beyond the daytime hours. Thermal energy storage can significantly increase the capacity factor of concentrated solar thermal power (CSP) plants from ~30% to greater than 60% which in turn can reduce the levelized cost of electricity (LCE). Thermal energy can be stored as either sensible or latent heat [1], although most of the thermal energy storage systems in operation are based on sensible heat storage. Storing energy in the form of latent heat of fusion of phase change material (PCM) in addition to sensible heat significantly increases the energy density resulting in a low storage capital cost per unit thermal storage capacity, commonly measured in \$/kWh$_t$. However, a major technology barrier that is limiting the use of latent thermal energy of PCM is the high thermal resistance provided by the intrinsically low thermal conductivity of the PCMs. Several efforts [2–6] to reduce the thermal resistance of PCMs are reported in the literature, which includes encapsulating PCM, packing PCM within a high thermal conductivity matrix, mixing high thermal conductivity particles into the PCM, use of extended surfaces, to name a few. Another approach is to embed heat pipes or thermosyphons in a latent thermal energy storage system (LTES) to enhance the heat transfer rate between the HTF and PCM [7–9].

The operation of a LTES constitutes the charging and discharging processes. During charging, hot heat transfer fluid (HTF) from the solar power tower enters the LTES and exchanges heat with the PCM, causing its melting at a constant temperature. As hot HTF enters the LTES tank, the existing cold fluid in the tank is forced out to return to the solar field. During discharging, cold fluid is pumped into the LTES resulting in the solidification of the PCM and the hot fluid exiting the LTES is directed to the power block for steam generation. It is to be noted that the direction of cold HTF inlet during discharging process is opposite to the charging process. The charging process takes place during the day when

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Nomenclature

c_p	specific heat [J/kg-K]
C^*	cost per unit mass [\$/kg]
C''	cost per unit area [\$/m^2]
h	convective heat transfer coefficient [W/m^{2}K]
h_{sl}	latent heat of fusion of PCM [J/kg]
H	height [m]
i	nodal point
k	thermal conductivity [W/m-K]
L	length [m]
$\dot{m}$	mass flow rate [kg/s]
N	number
Q	energy [J]
r	radius [m]
S_L	longitudinal spacing [m]
S_T	transverse spacing [m]
T	temperature [K]
T_m	PCM melting temperature [K]
t	time [s]
U	velocity [mm/s]
w	thickness [m]
W	width [m]

Subscripts and superscripts

a	adiabatic
c	condenser
C	charging
d	channel
D	discharging
e	evaporator
HP	heat pipe
w	wick
x	computational cells in x-direction

Greek symbols

α	storage cost [\$/kWh$_t$]
β	thermal expansion coefficient [K^{-1}]
φ	wick porosity
μ	dynamic viscosity [kg/m-s]
ρ	density [kg/m^3]
γ	liquid fraction

solar energy is available while discharging is effected whenever the sun is not available or when there is a peak demand in electricity. The charging and discharging process combined is referred to as one cycle and repeated cycles subjected to partial charging and discharging process is the typical operation mode of a LTES.

To address the poor thermal conductivity of the PCM, use of embedded heat pipes or thermosyphons between the PCM and the HTF has been explored in the literature as a means of enhancing the thermal energy transport: Horbaniuc et al. [10] 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. [11] 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. [12] used a thermosyphon to investigate its sensitivity on a variety of PCMs. Tardy and Sami [13] 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. Two recent publications [14,15] presented the use of embedded heat pipes in PCM for a LTES application. The studies considered a shell and tube configuration and numerical analysis conducted based on thermal resistance network modeling provided a quick estimate of the qualitative trends in the performance with respect to the various operational and design parameters. The analysis was performed for a small module of the large LTES system and the results obtained may not be applicable at the system level commensurate with a CSP plant operation.

The U.S. Department of Energy SunShot Initiative seeks to bring the levelized cost of energy of concentrating solar power to be on par with that for conventional generation sources [19]. According to the SunShot vision study [19], integrating a thermal storage system along with technological breakthroughs in other subsystems of the CSP plant has the potential to reduce the levelized cost of electricity generated from CSP to as low as 6 ¢/kWh comparable to fossil-fueled electric power generation. In developing thermal storage technologies, round-trip energy efficiency is often cited as a key metric of performance; however, the *exergetic* efficiency is a more important parameter that needs to be high to ensure that heat quality is maintained after storage [1]. Previous investigations on LTES have shown that cascading several PCMs in the order of decreasing melt temperatures from the hot HTF inlet side can result in higher heat transfer rates, as well as improved exergetic efficiency due to a more uniform temperature difference between the hot and cold media [16–18]. An optimal design of a HP-TES system for integration into CSP plants should have round-trip exergetic efficiency greater than 95% and a storage capital cost less than \$15/kWh$_t$ for a minimum discharge period of 6 h, as per the U.S. Department of Energy SunShot Initiative requirements. Designing the latent thermal energy storage system with embedded heat pipes to meet these techno-economic targets, therefore, forms the focus of the present study.

While modeling of the LTES system with heat pipes has been reported in the literature and provides insight on HP-TES operation [14,15], a systematic study to quantitatively determine the optimal design parameters from physics based modeling is lacking. In view of this, a methodology for model based design and optimization is presented for the first time based on the systematic parametric studies and consideration of the U.S. Department of Energy SunShot requirements [19] on the dynamic operation of the system. Based on the parametric studies and specified constraints on the minimum exergetic efficiency, maximum storage capital cost and minimum discharge time, operating windows are identified on the HTF velocity as a function of the various design parameters for non-cascaded and 2-PCM cascaded HP-TES system configurations.

The paper is organized as follows: The mathematical model is described in the next section followed by a discussion of the results of the parametric studies in Section 3.

2. Numerical analysis

2.1. HP-TES numerical model

The HP-TES system configuration considered in the present model is shown in Fig. 1a. The HTF flow to the storage system is divided equally among the N_d channels where the heat transfer between the HTF and PCM takes place. The schematic of one channel